Eyes on the Extreme Universe:

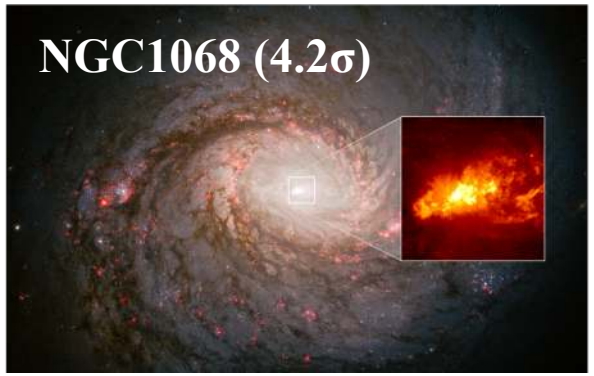
Neutrino Telescopes across the Globe

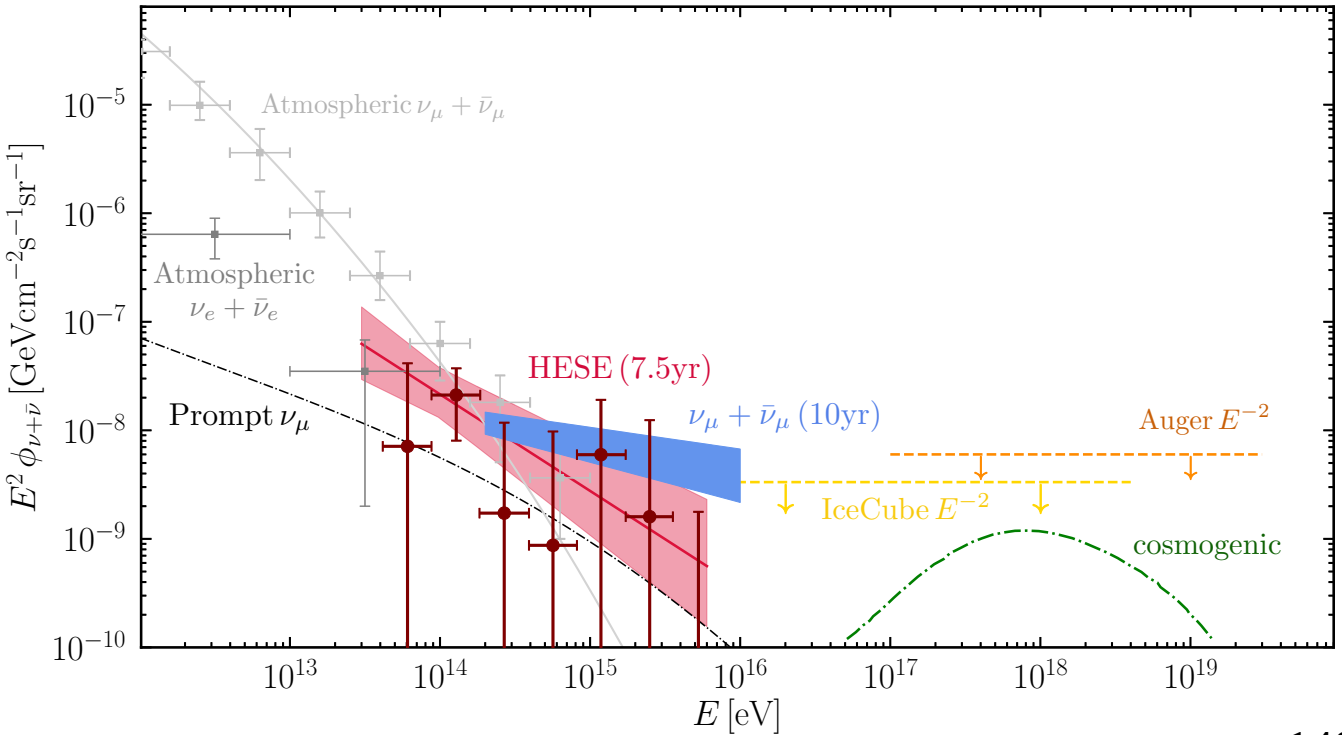
Donglian Xu (TDLI)

CRIS-MAC 2024

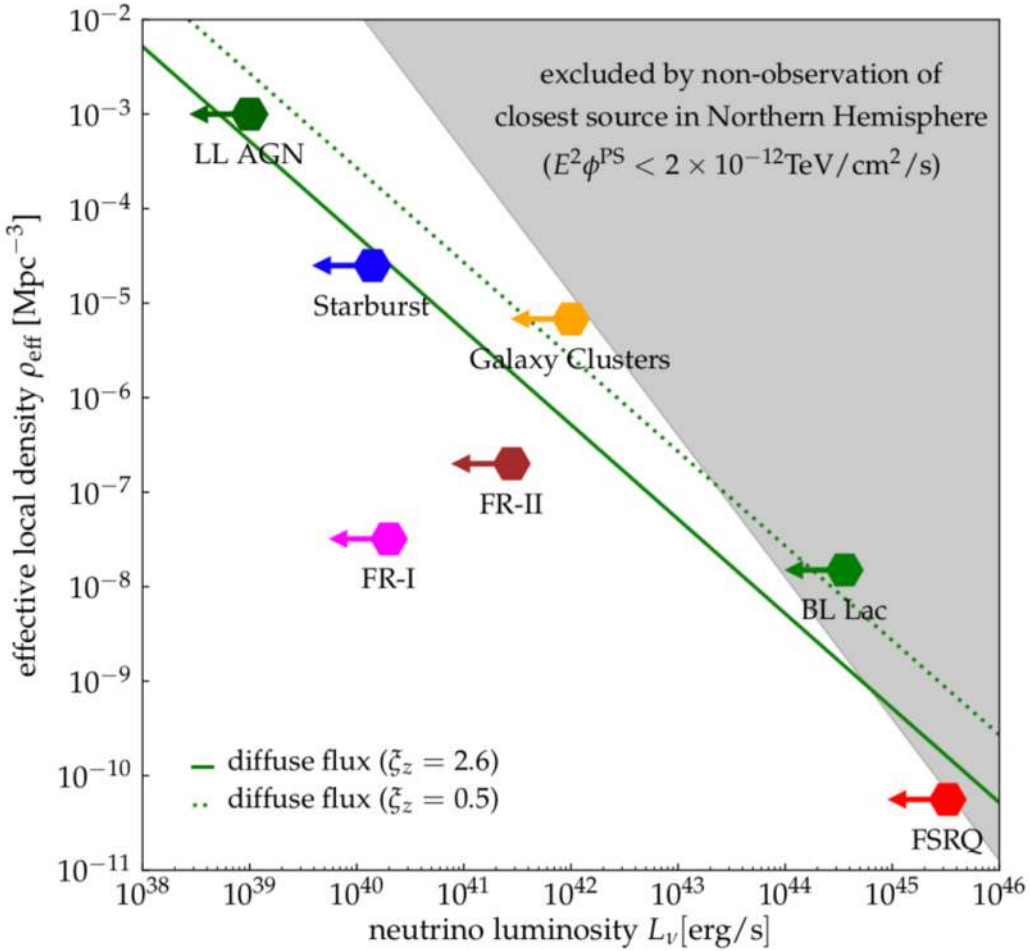
2024.06.18 | Sicily, Italy

A new era of neutrino astronomy



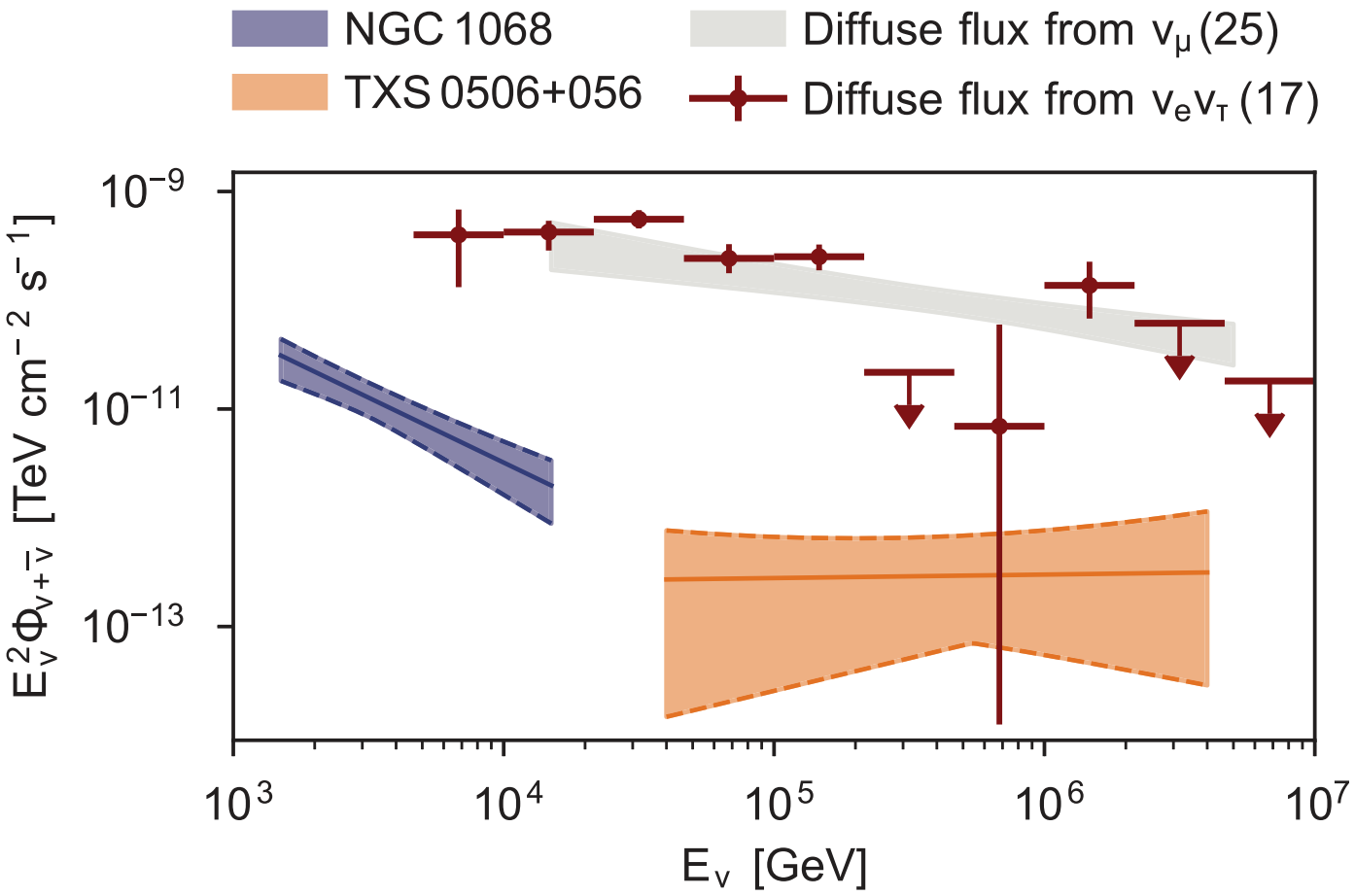


Halzen & Khierandish, arXiv:2202.00694



< 14% of the diffuse flux can come from the Galaxy

Astrophysical ν sources



IceCube Collaboration, **Science** 378, 538 (2022)

- **At least two distinctive categories of sources**
- **Diffuse flux largely unresolved**

↓

1) How to **optimize** next-gen neutrino telescopes for **low** and **high energies?**

2) Room to **improve** on **angular resolution?** Need better than 0.1° @ 100TeV to resolve the diffuse flux

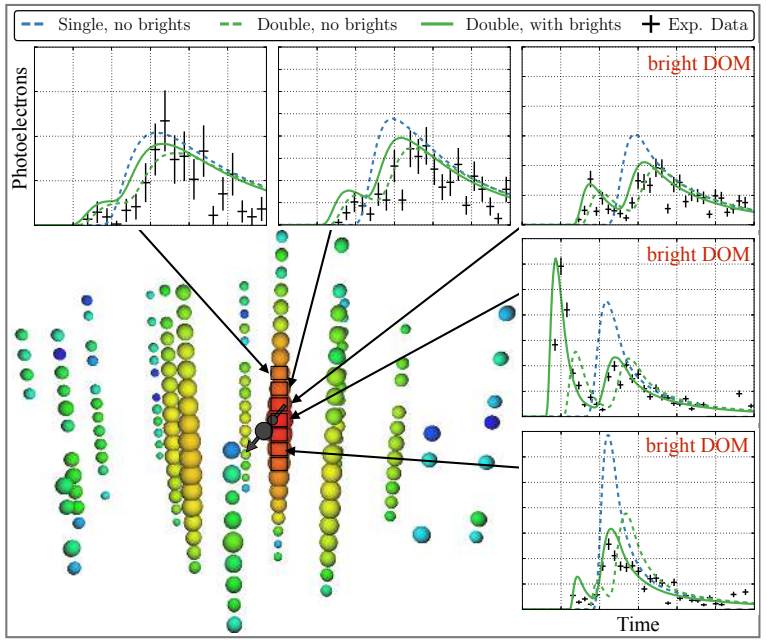
3) How to **boost flavor identification** for discovered sources**?**

Astrophysical ν flavor identification

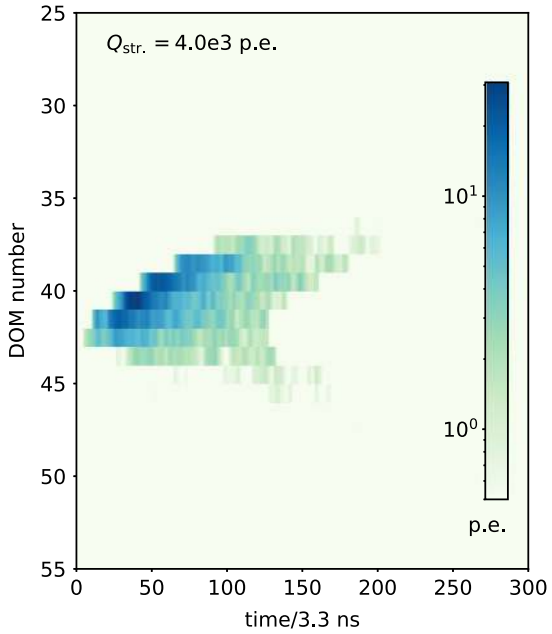
How can we improve? →

1) **Larger detectors** for more high-energy events

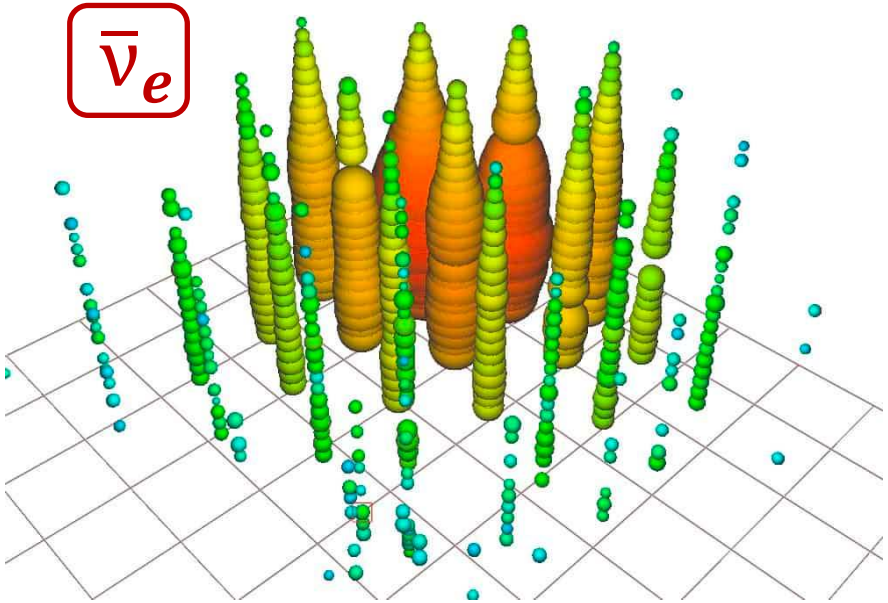
2) **Pixelized DOMs with waveforms** for recording kinetic info



ν_τ



$\bar{\nu}_e$



IceCube Collaboration, *Eur. Phys. J. C* 82, 1031 (2022)

M. Meier, J. Soedingrekso, PoS (ICRC2019) 960

L. Wille, D.-L. Xu, PoS (ICRC2019) 1036

IceCube Collaboration,

Phys. Rev. Lett. 132, 151001 (2024)

IceCube Collaboration,

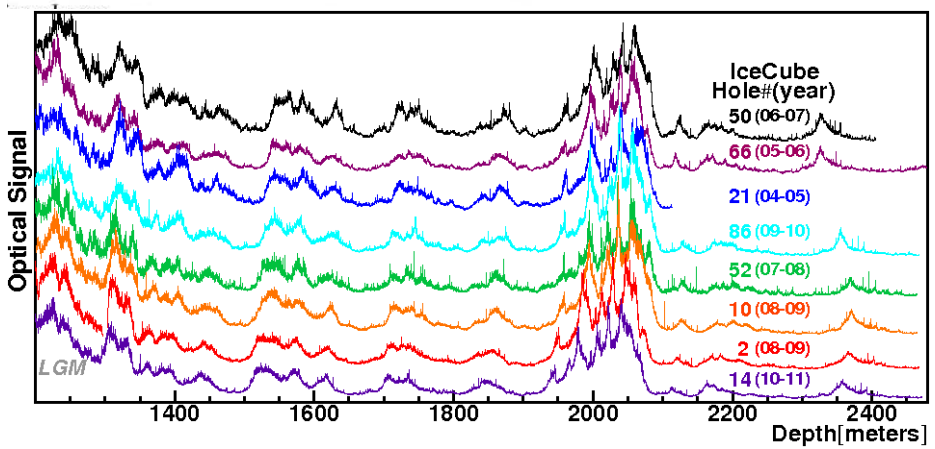
Nature 591, 220–224 (2021)

(Next-gen) neutrino telescopes under planning

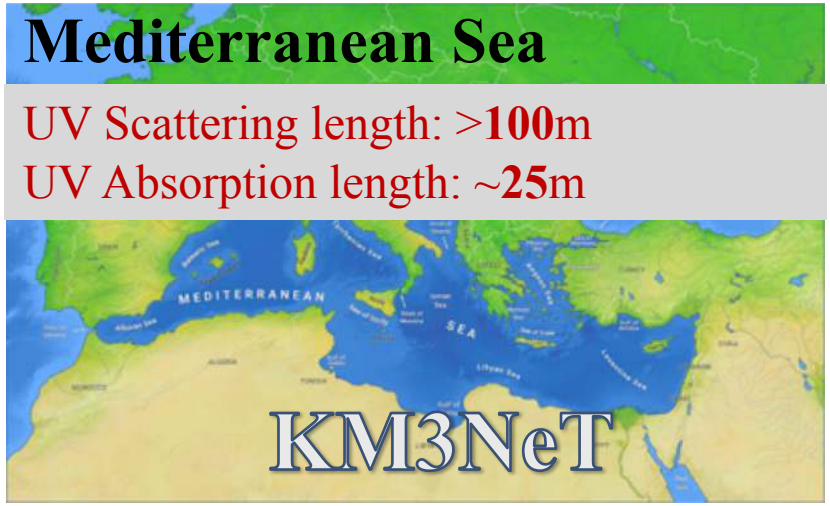
Interaction medium: Ice vs Water

Glacial ice

Most transparent medium on Earth!
Scattering length: ~**25**m
Absorption length: >**100**m



Lake/sea water



On average, ice is more transparent / less absorbing, while water is less scattering

⇩

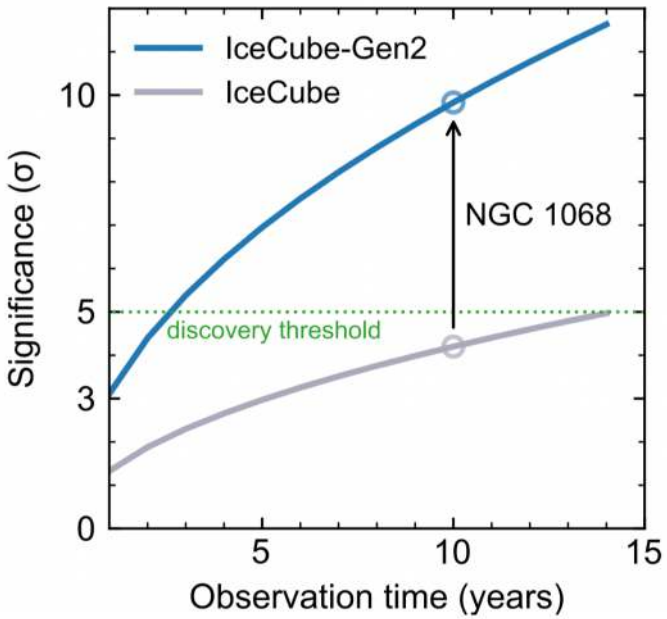
More "direct" photons in water-based telescopes → intrinsically better pointing can be achieved

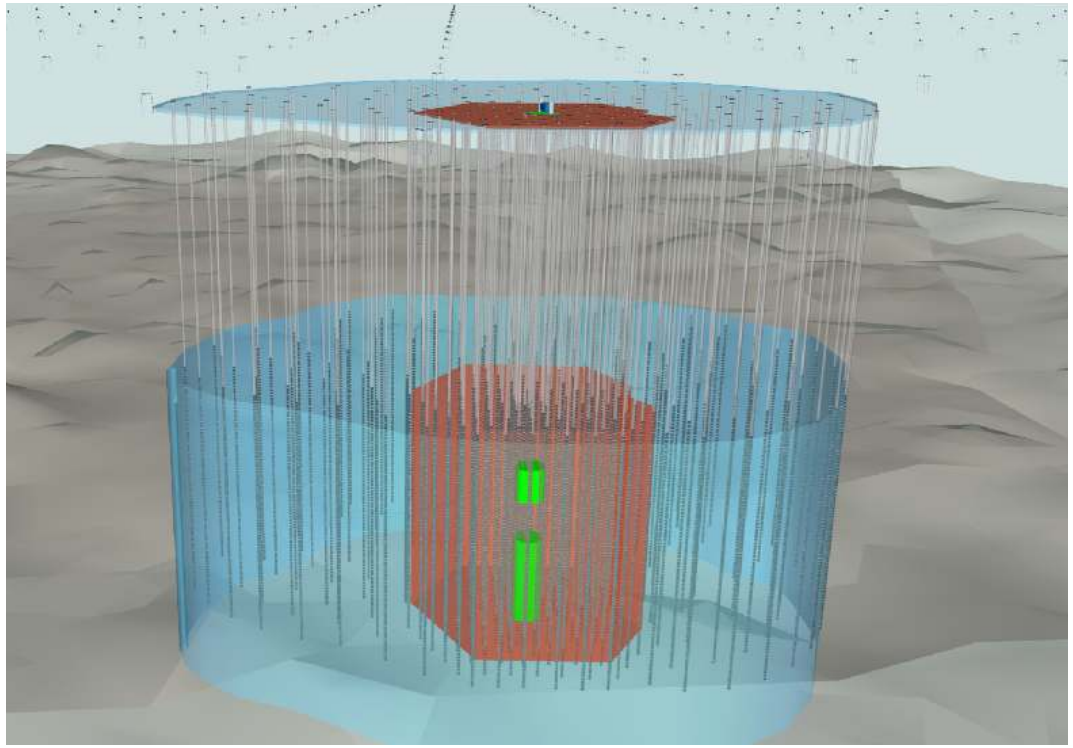
IceCube-Gen2

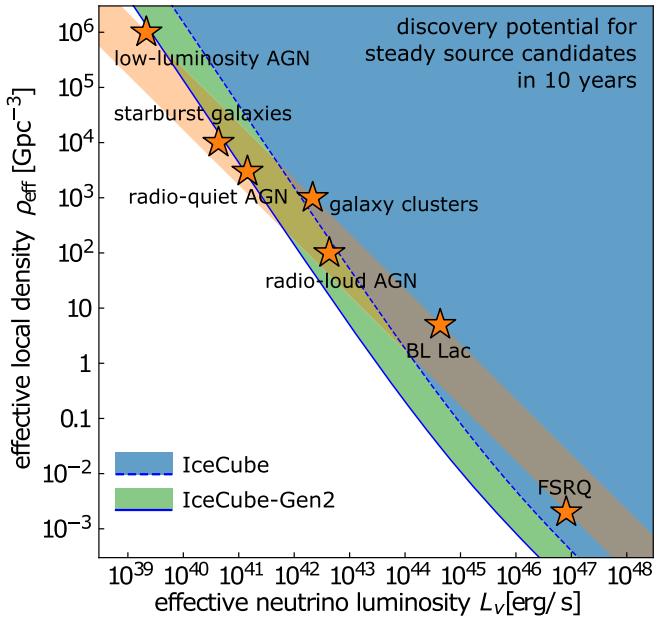
10 km^3 + 500 km^2 surface array for radio UHE neutrinos

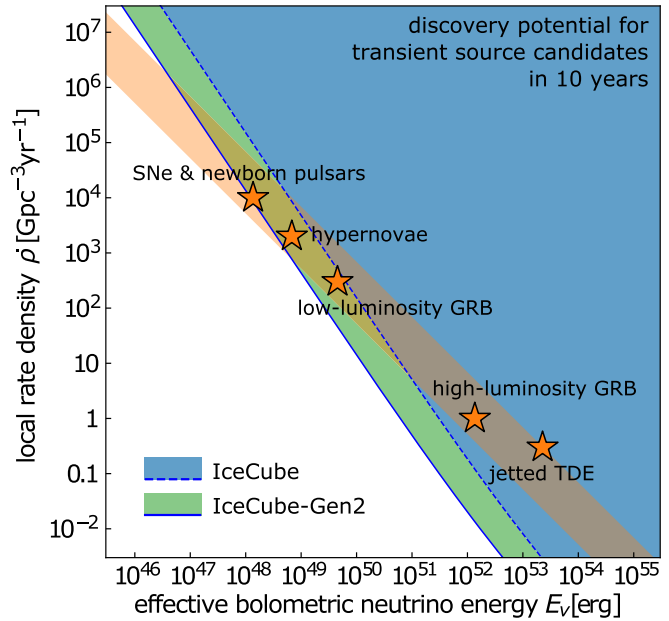
~5 times improvement in **point source sensitivity**

Timeline: **~2035 / 2038**



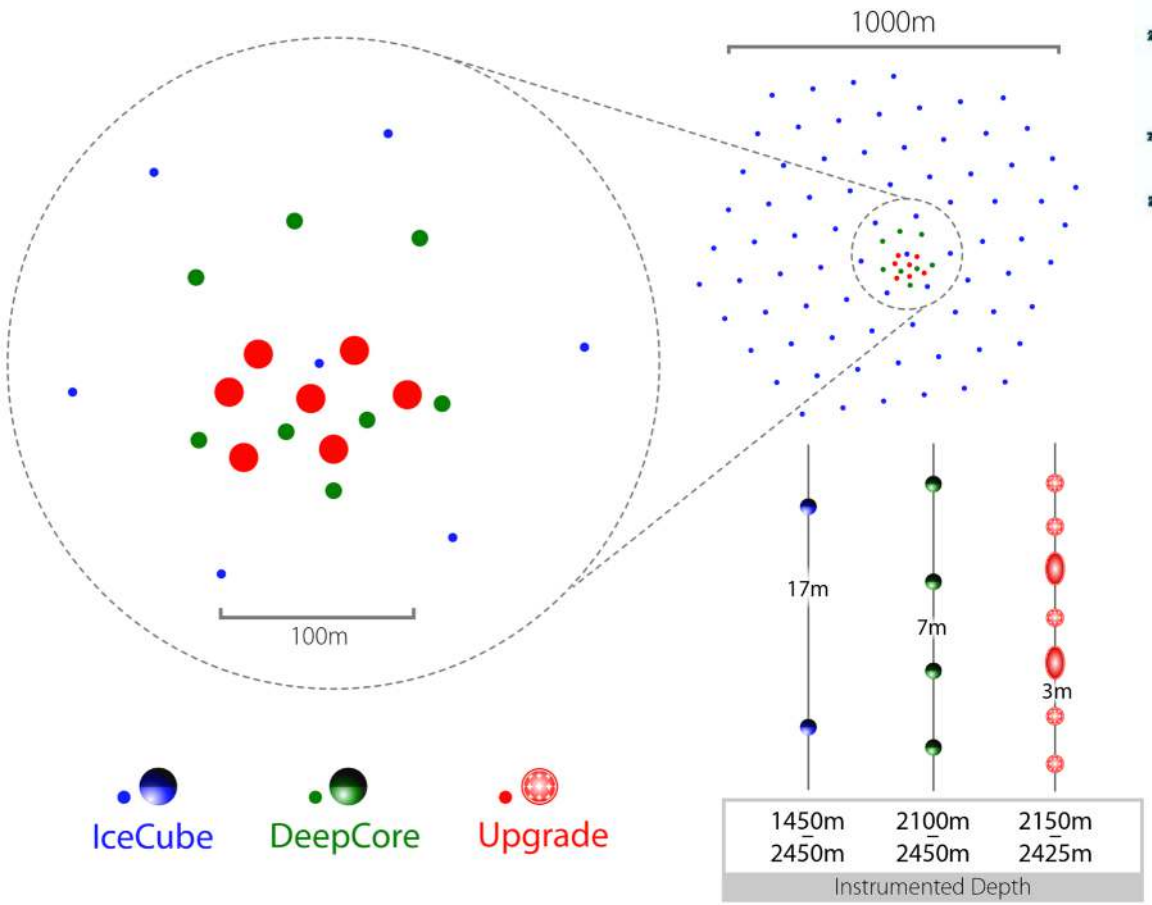


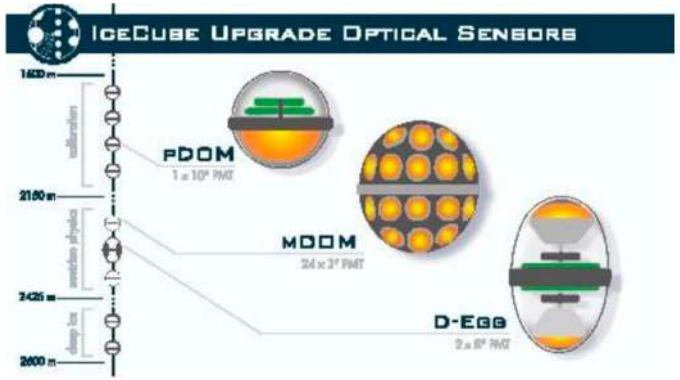




J. Phys. G: Nucl. Part. Phys. 48 (2021) 060501

IceCube-Upgrade Status



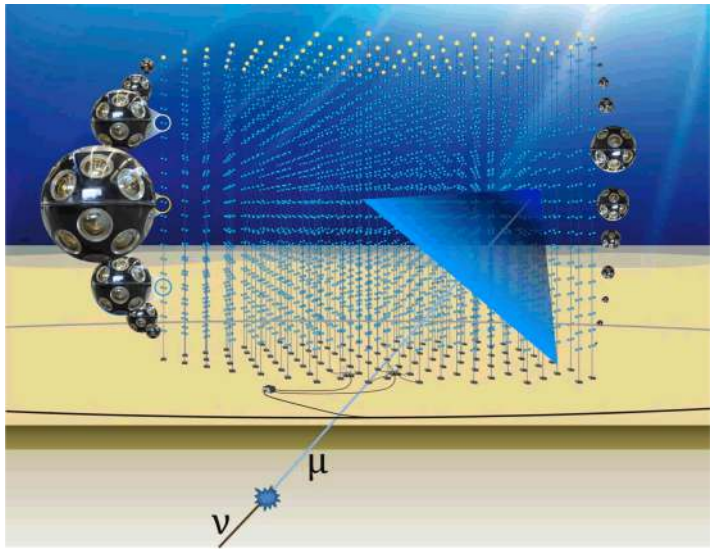


- Seven new in-filled strings
- Better efficiency and reconstruction at low energies
- Improved calibration of ice, reduced systematic uncertainties
  - Improved angular and energy reconstructions at all energies.
- Goals:
  - Precision measurement of atmospheric neutrino oscillations.
  - Re-processing of TeV data.
- Delayed due to Covid-19: deployment in 2025/26 season.

Courtesy: J. A. Aguilar @ Neutrino 2024

Water-based neutrino telescopes under construction

KM3NeT ARCA

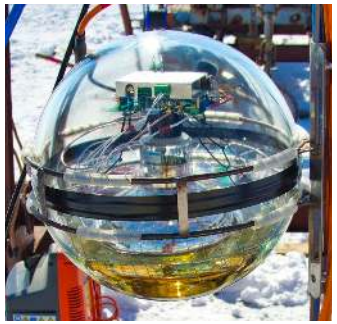


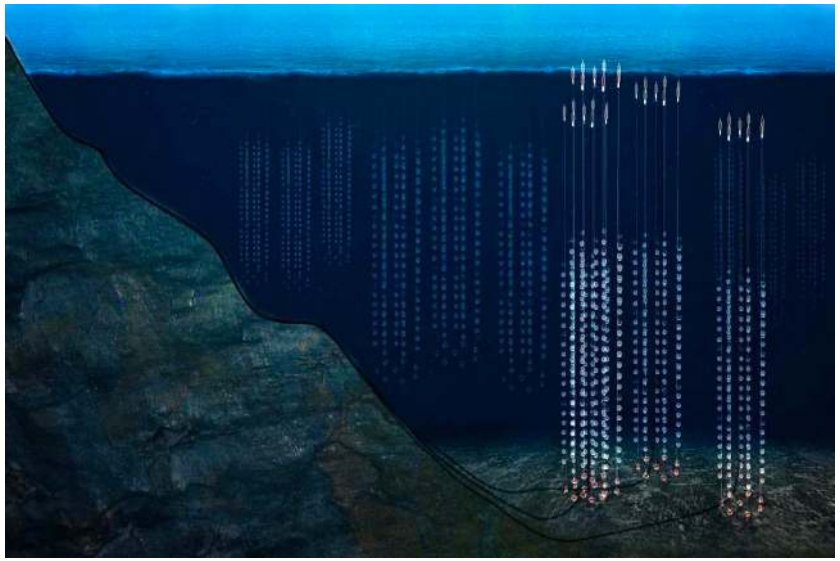
230 strings

Reaching **~1km³**

Timeline: **2028**

Baikal-GVD



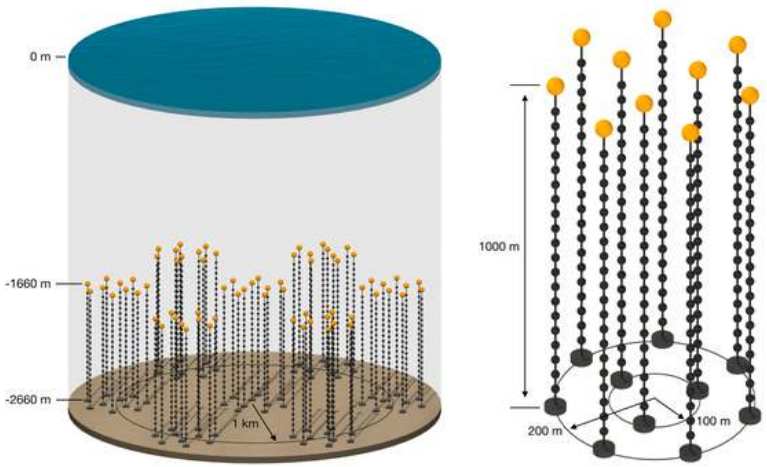


total **16-18 clusters**

Reaching **~1km³**

Timeline: **~2025/2026**

P-One



70 strings

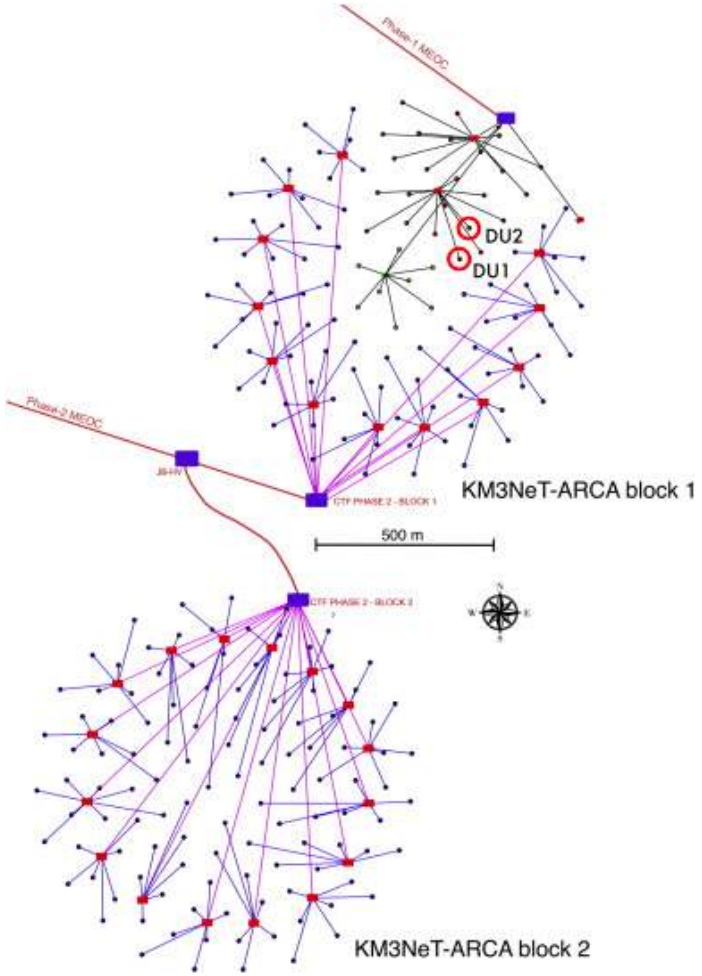
Reaching **km³** volume

Timeline: **~2035**

KM3NeT-ARCA Status

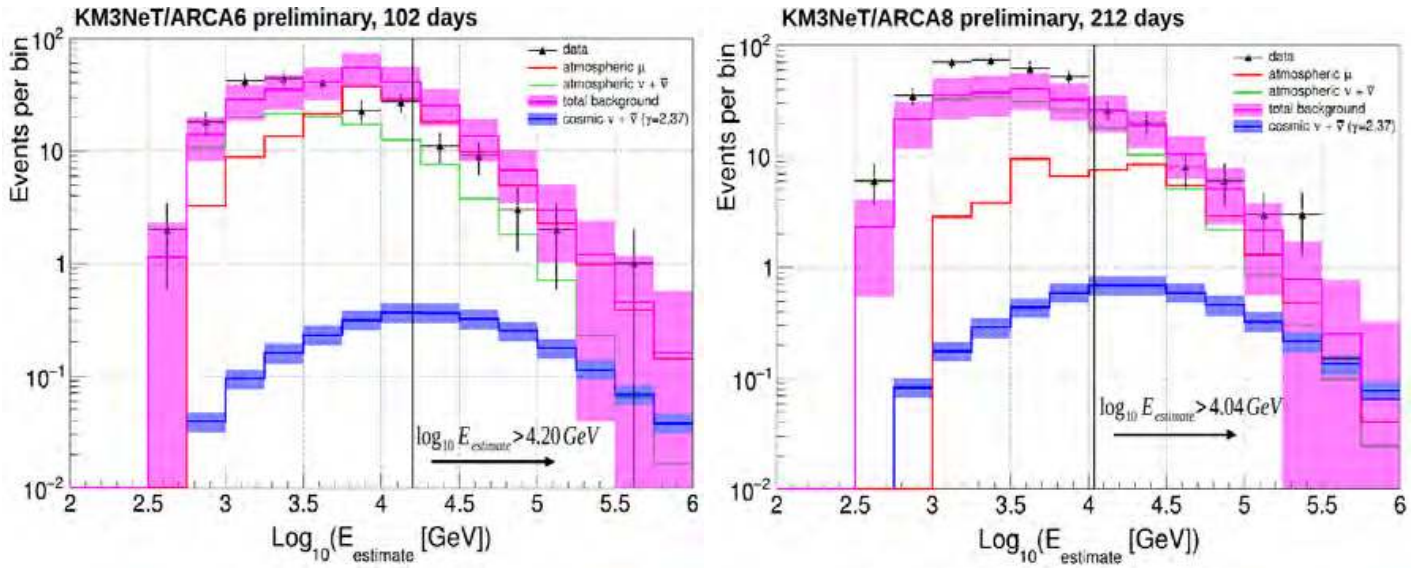
See Rosa Coniglione's talk at this conference

21 strings (DUs), **378** mDOMs since 2021 (as of ICRC2023)



- ***Up-going*** events with partial detector collected between 2021 and 2022
- Setting upper limits in unit of $\mathbf{10^{-18}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$

	ARCA6+8	ARCA19+21	ARCA6+8+19+21	ANTARES	5% quantile	95% quantile
$\gamma = 2.0$	5.11	3.13	2.09	4.0	15.07 TeV	11.71 PeV
$\gamma = 2.37$	6.92	4.68	3.06		5.88 TeV	1.73 PeV
$\gamma = 2.5$	6.76	4.94	3.12	6.8	4.43 TeV	1.03 PeV



POS(ICRC2023)1195

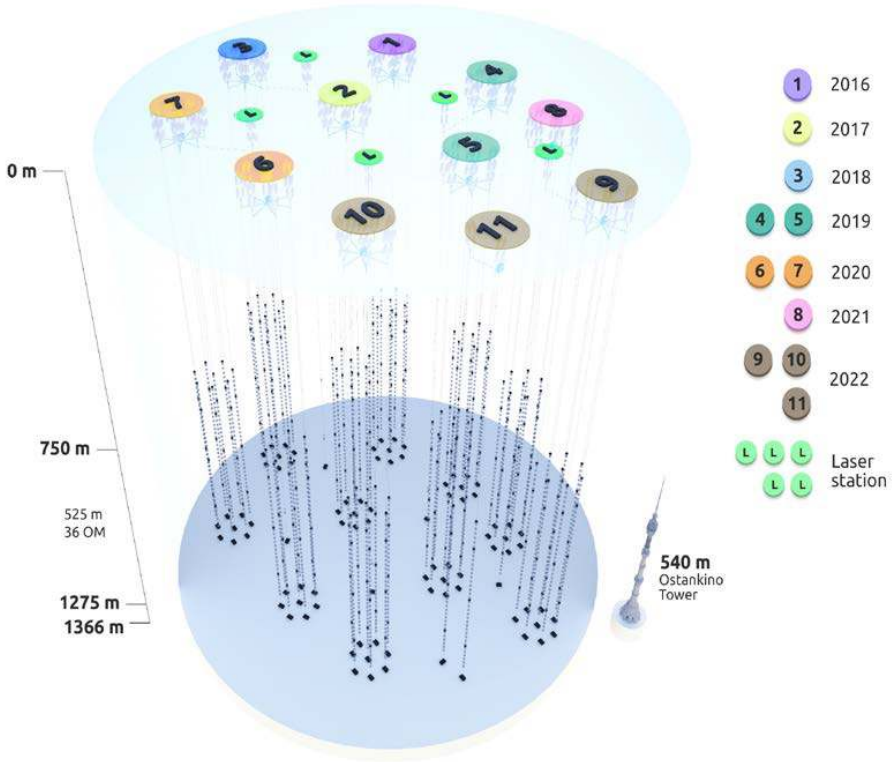
Baikal-GVD Status

Now largest neutrino telescope in the North!

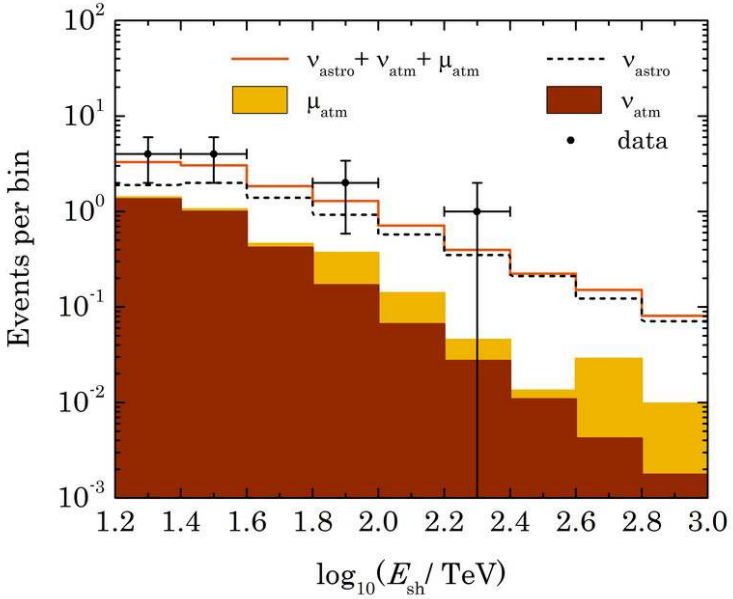
Construction started in 2016

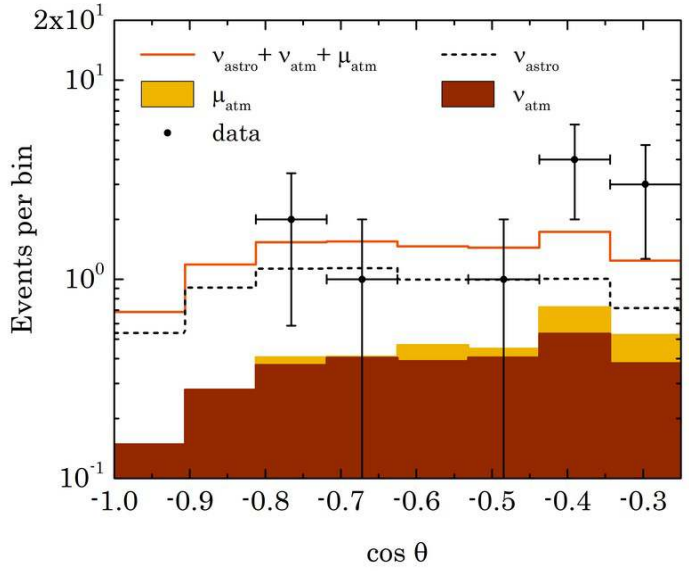
12 clusters, **96** strings, **3456** DOMs

→~**50%** IceCube volume (2023)



- **Cascade** events with partial detector collected between 2018 and 2022
- **17** events over 4.4 expected atmospheric bg
- Confirmed the IceCube diffuse flux at **3σ level**

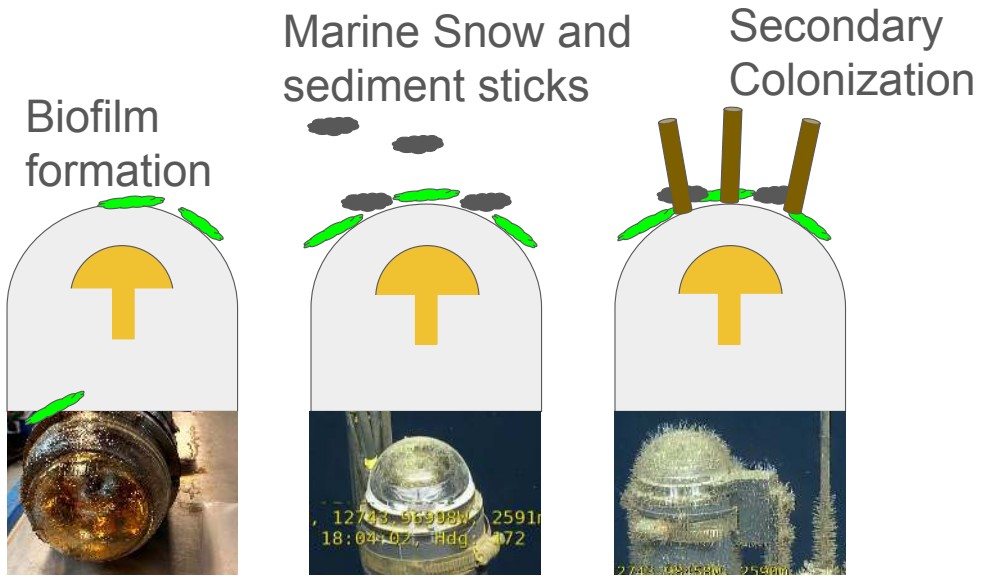


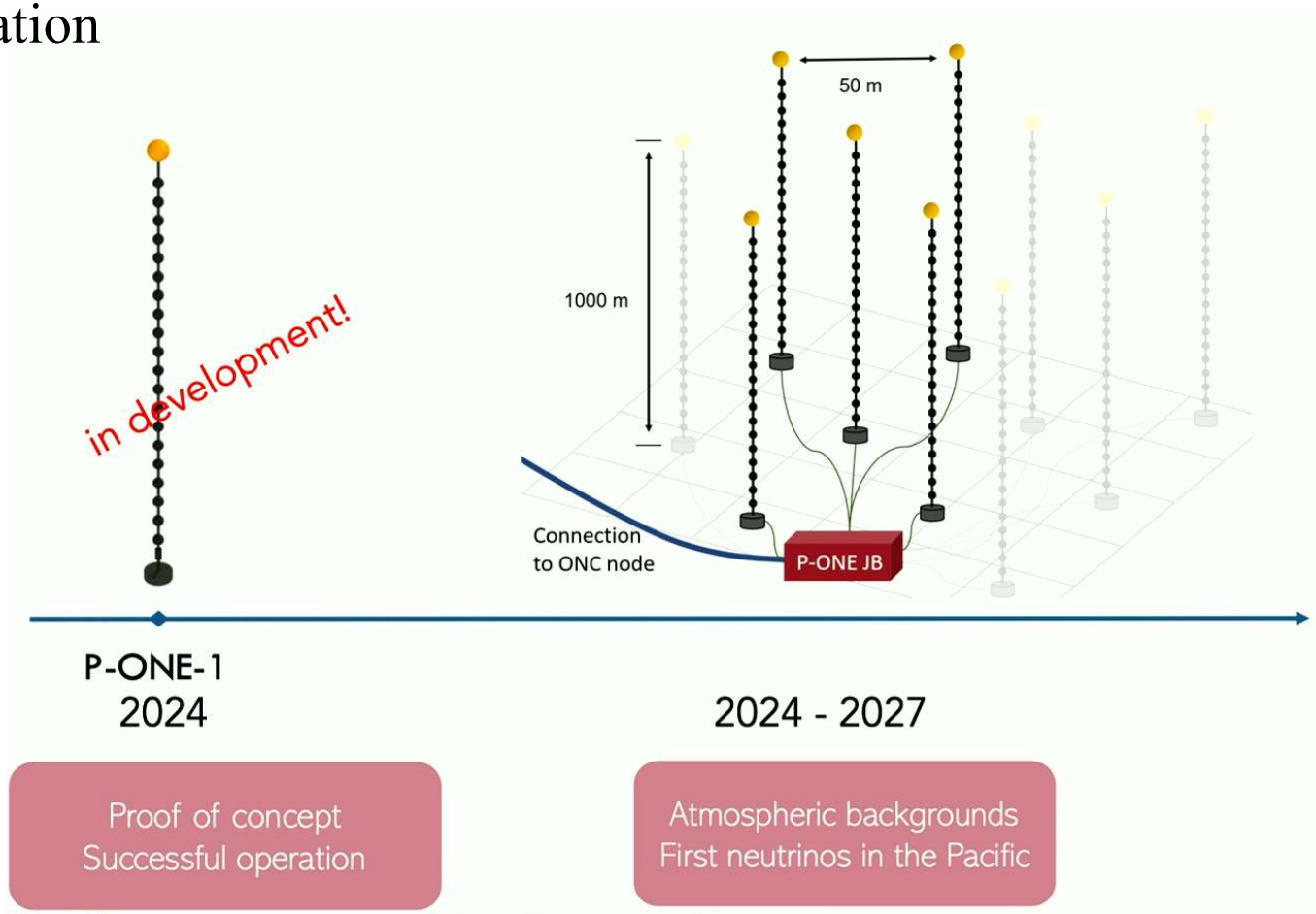


POS(ICRC2023)1015

P-ONE Status

- Biofouling and sedimentation characterization & monitoring:
  - CMOS camera with a fish-eye lens
- Real-time calibration systems:
  - Flasher beacons → water dispersion
  - Diffuse flasher → attenuation properties
  - Acoustic receivers → position calibration

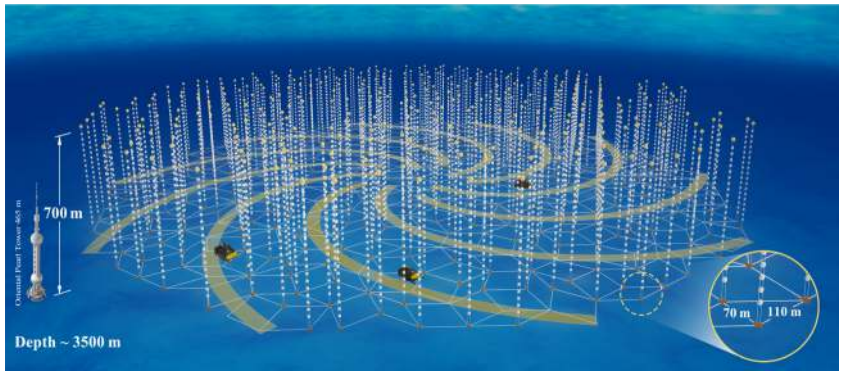




Courtesy: Matthias Danninger @ Pirsa 2023

Neutrino telescopes under planning in China

TRIDENT



1200 strings, reaching **~8 km³**

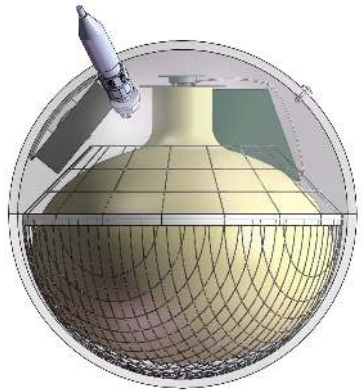
Timeline: ~**2030-2035**

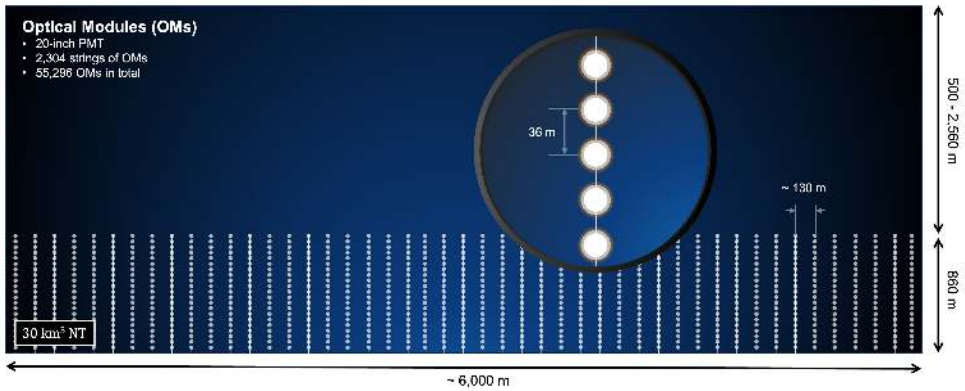
Location: South China Sea

Nature Astronomy (2023)

HUNT

(> 100 TeV)





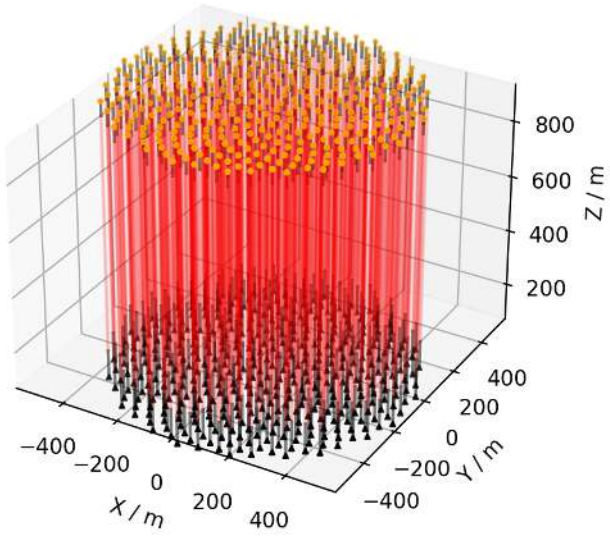
2304 strings, reaching **~30 km³**

Timeline: **???**

Location: Lake Baikal / South China Sea

POS(ICRC2023)108

NEON



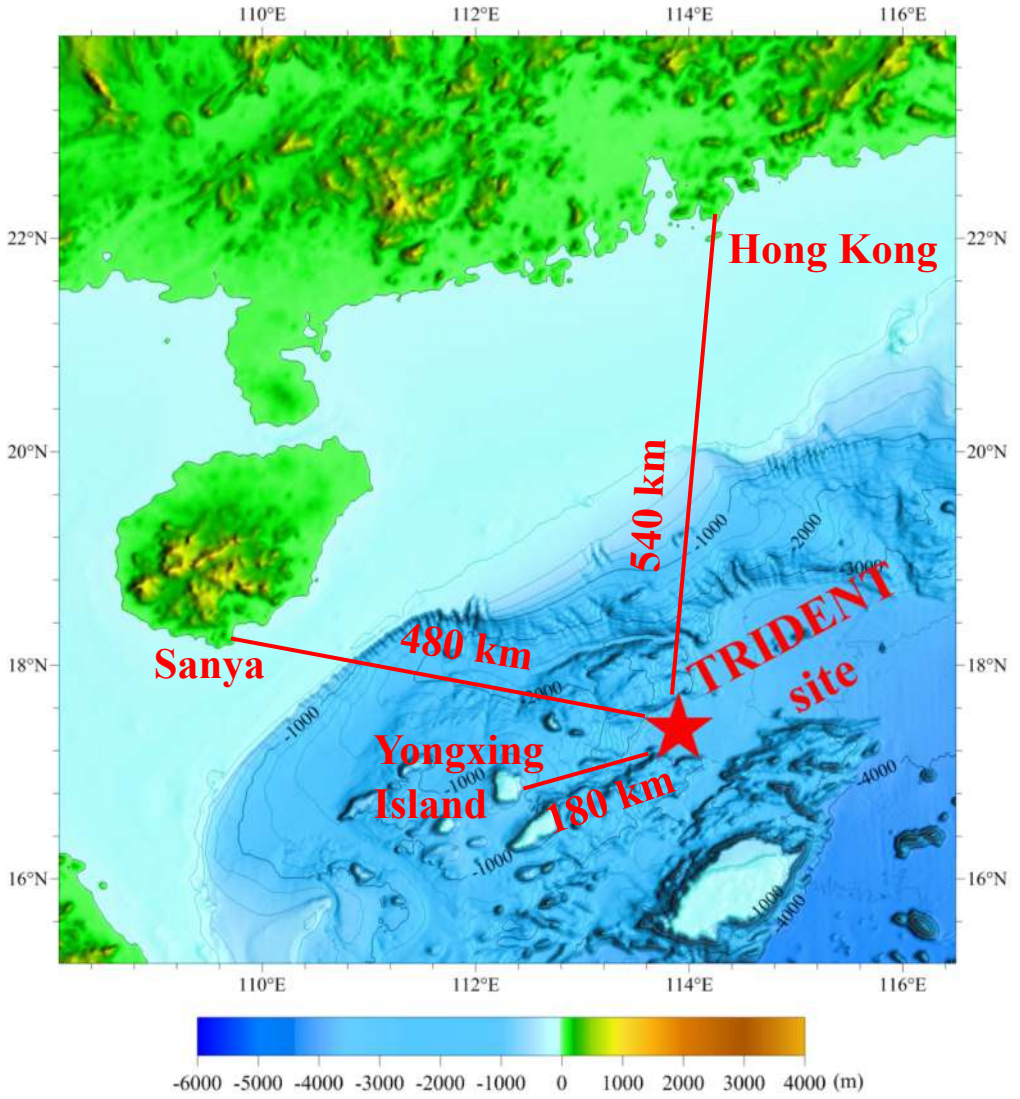
400 strings, reaching **0.8 km³**

Timeline: **???**

Location: South China Sea

POS(ICRC2023)1017

TRIDENT Explorer : T-REX



Pre-selected site conditions

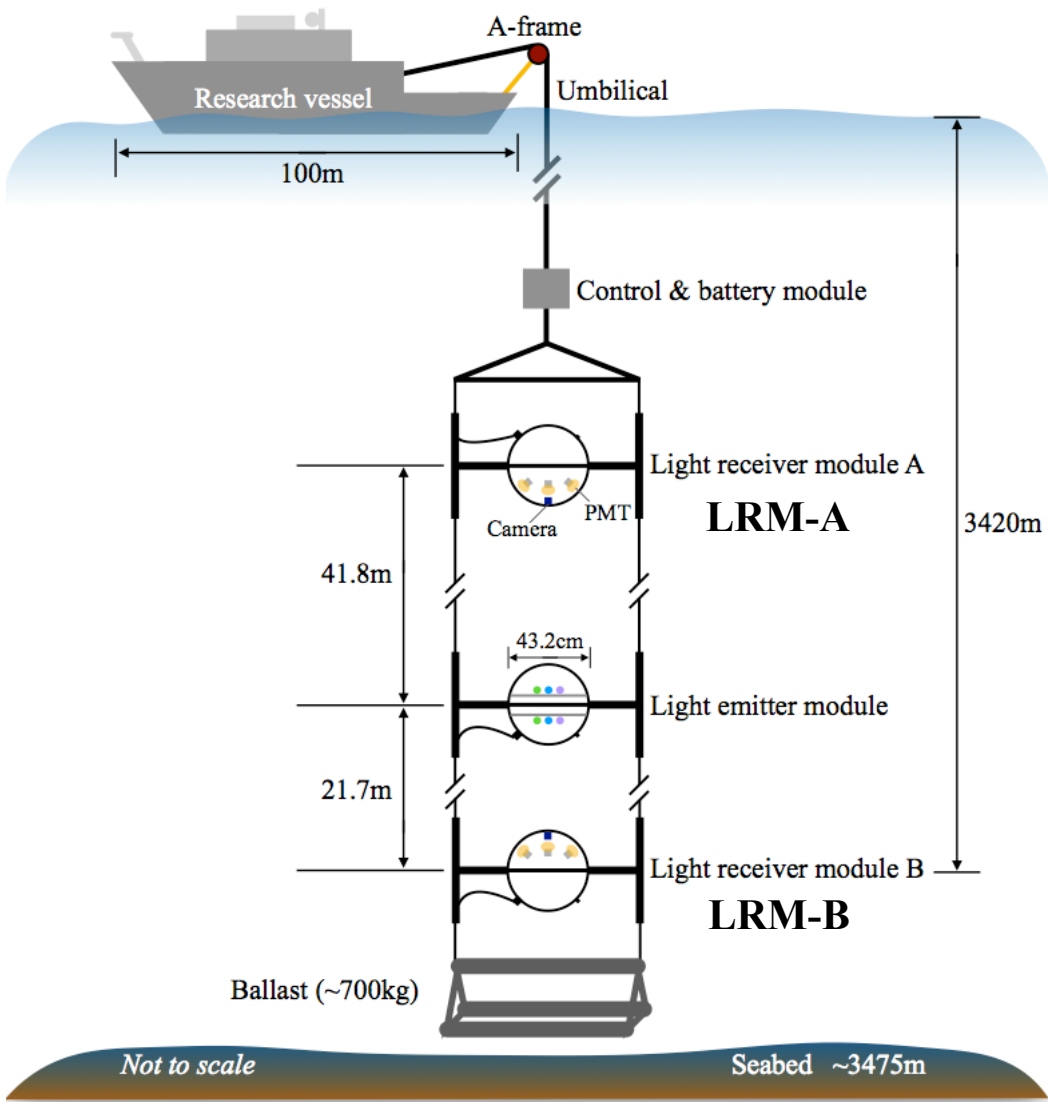
- Flat seabed
- No nearby high rises or deep trenches
- Depth >3km
- Close proximity to a shore

Measured params

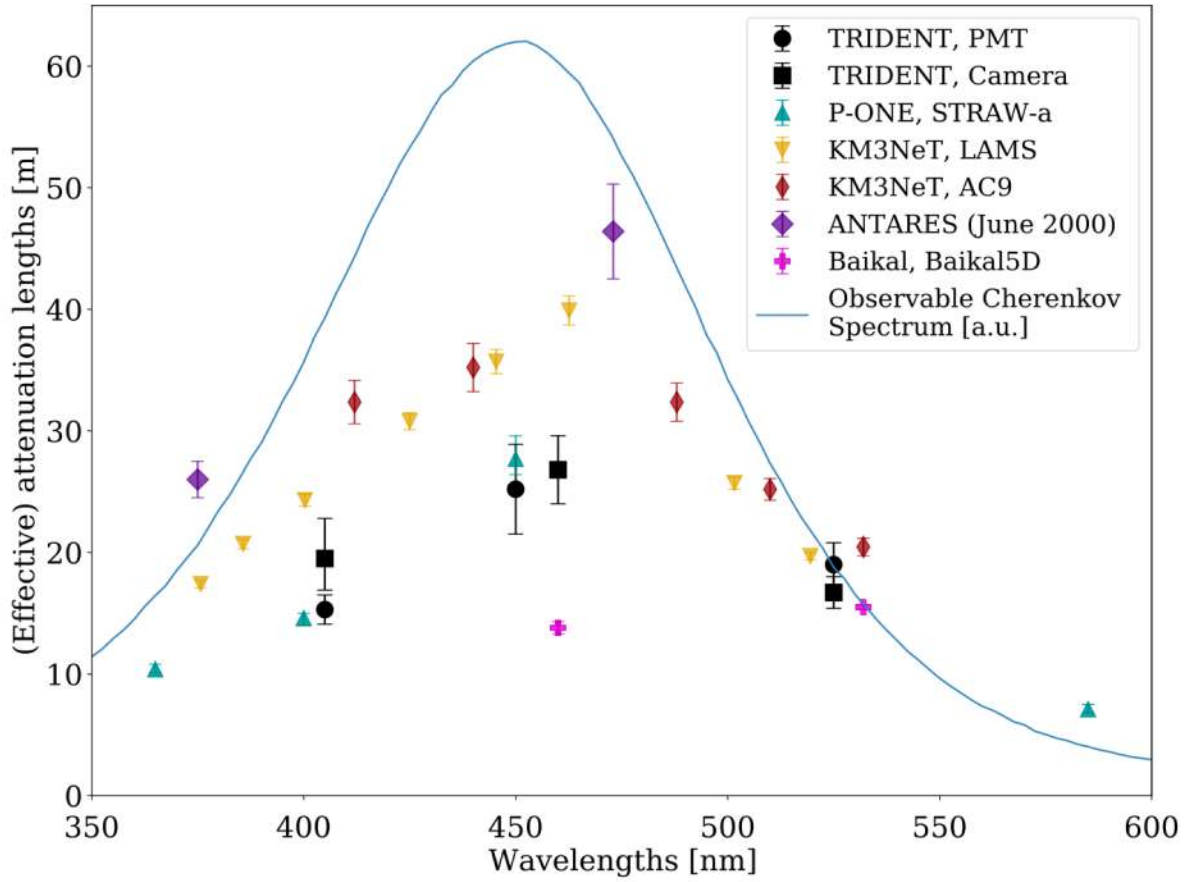
- **Optical properties**
- Current field
- Radioactivity

https://trident.sjtu.edu.cn/en

TRIDENT Explorer : Optical Properties

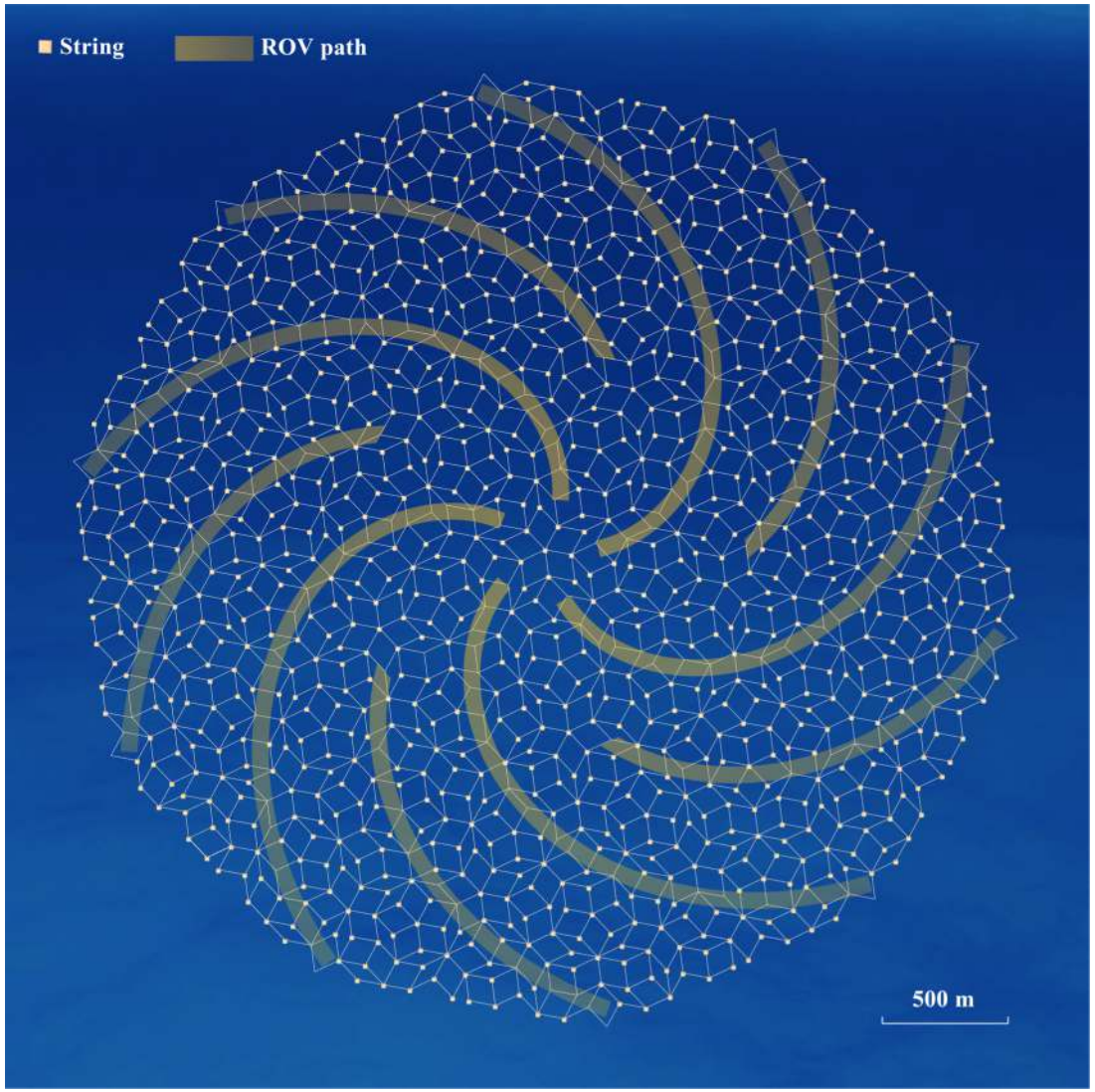


- Dedicated analytical and numerical modeling
- Exp. data: ~ **1**TB ⇔ Simulated data: ~ **100** TB, **10M** files



Nature Astronomy 7, 1497-1505 (2023)

TRIDENT detector geometry



Penrose tiling layout

Uneven inter-string spacing **70m** and **110m**

→ expanded energy window of **sub TeV – EeV**

No translational or rotational **symmetry**

→ better rejection of "corridor" atmo. muons

1200 strings; **20** hDOMs / string

Volume: ~ **8** km^3

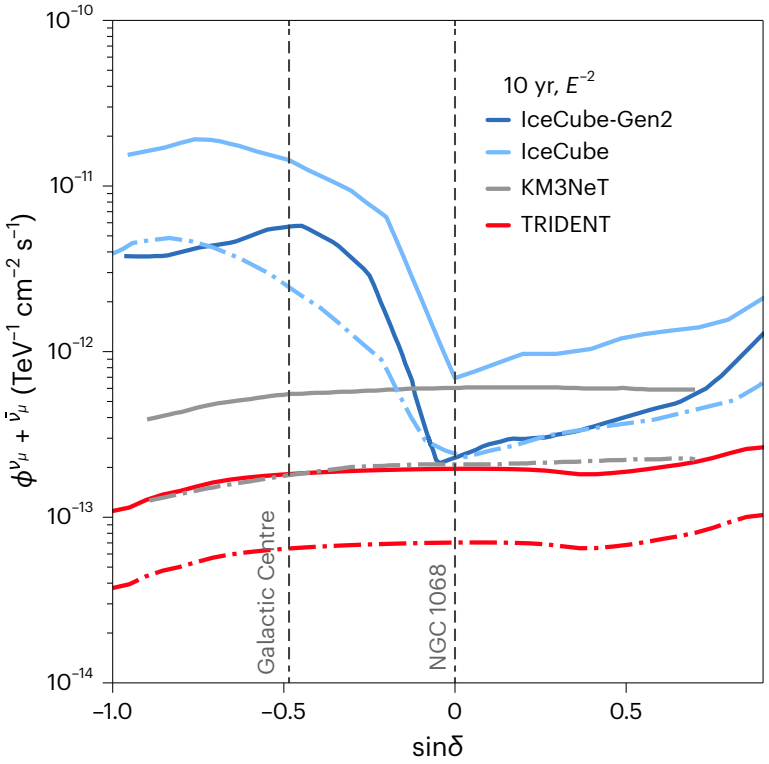
Underwater ROV for deployment & maintenance

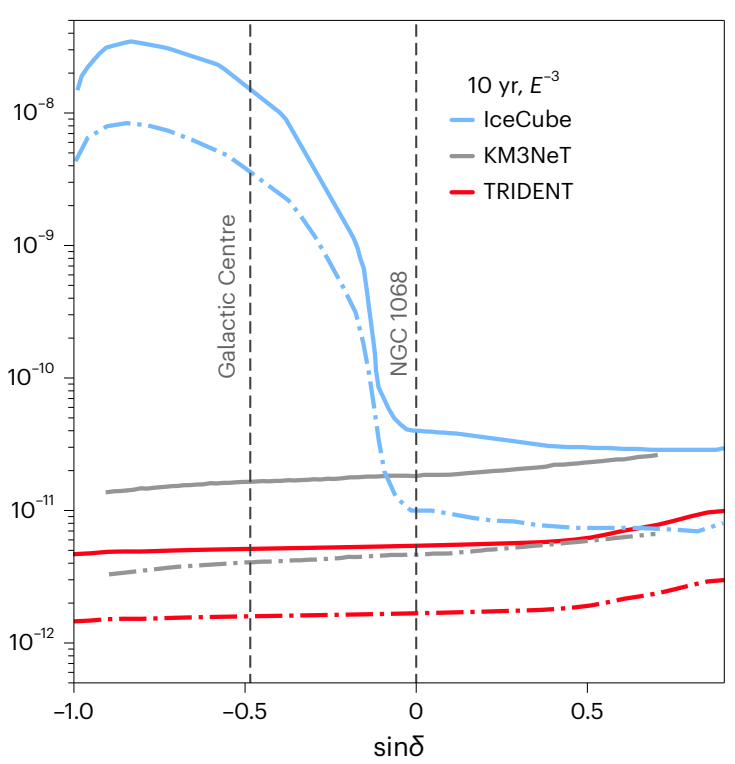
Nature Astronomy 7, 1497-1505 (2023)

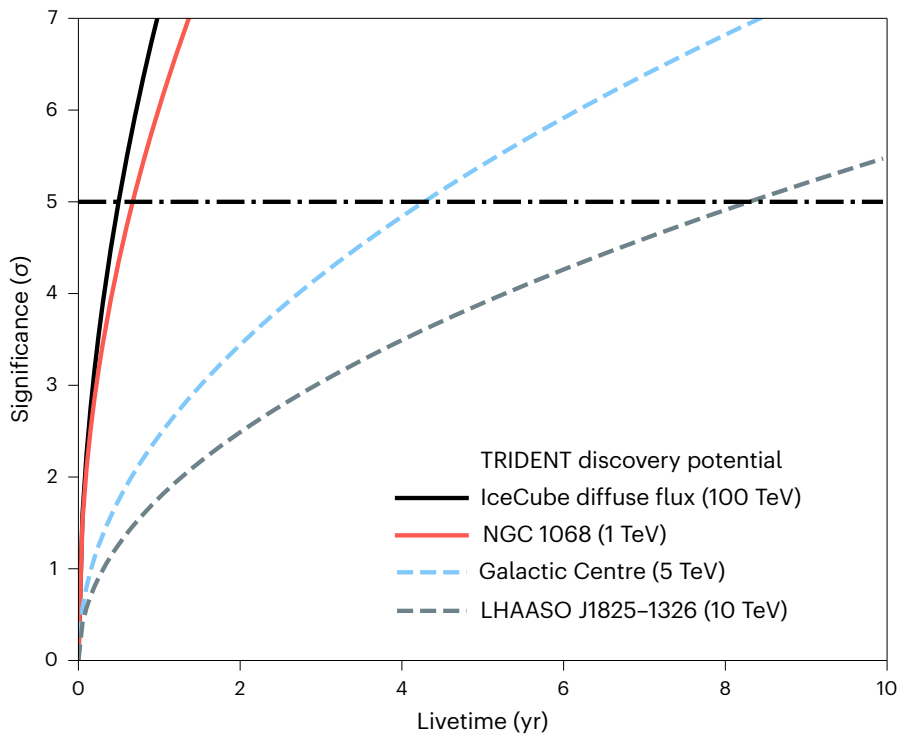
Geometry comparison: PoS (ICRC2023) 1203

TRIDENT Source sensitivity & discovery potentials

Track events only







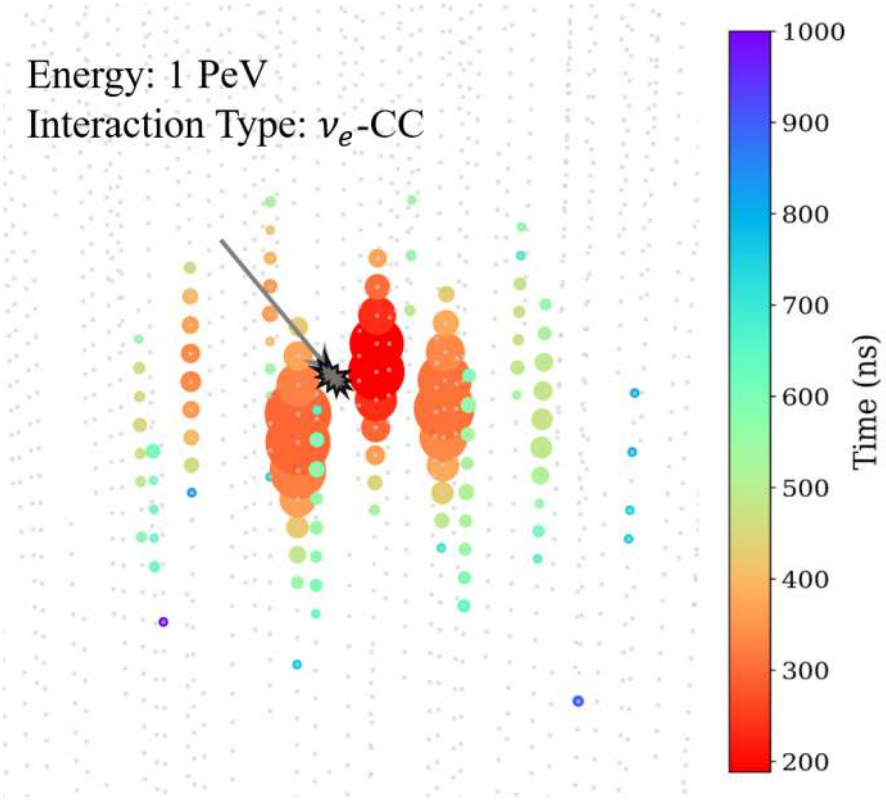
TRIDENT is expected to detect the IceCube steady source candidate NGC1068 at 5σ level within one year of operation

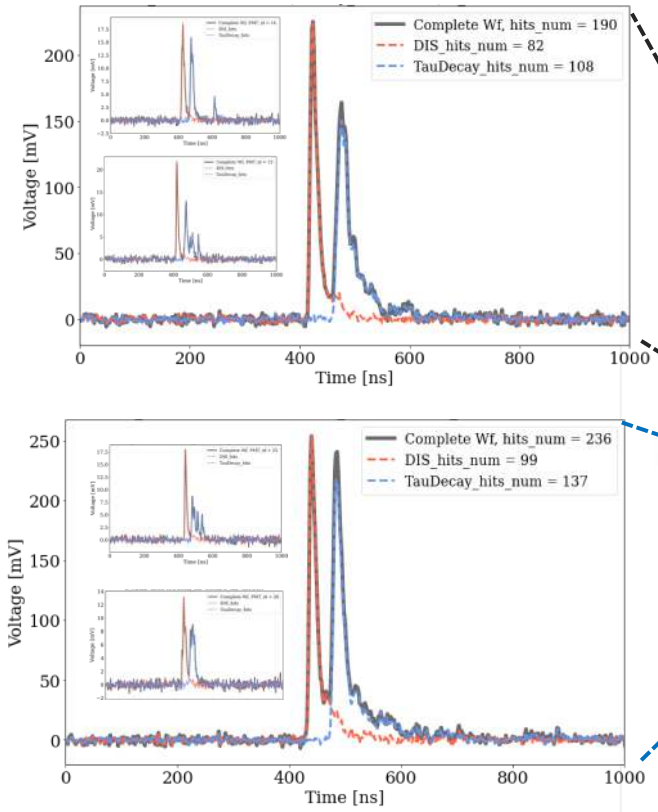
Nature Astronomy 7, 1497-1505 (2023)

TRIDENT Sensitivity to all neutrino flavors

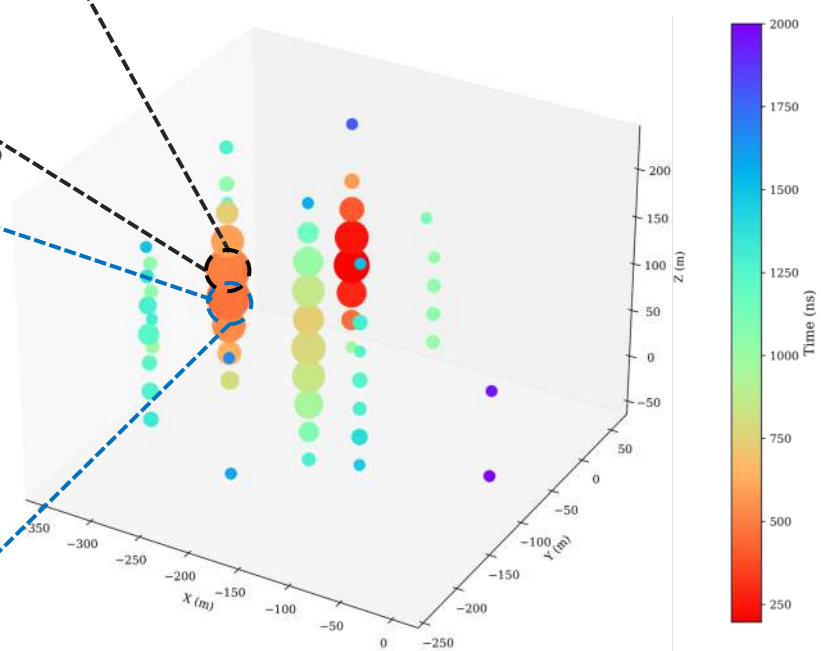
Angular resolution for cascades:
- **~1.8° @ 1PeV** (likelihood)
- **~ 1.5° @ 100 TeV & 1 PeV** (GNN)

Where are the ν_e and ν_τ from NGC 1068 and TXS 0506+056 ?





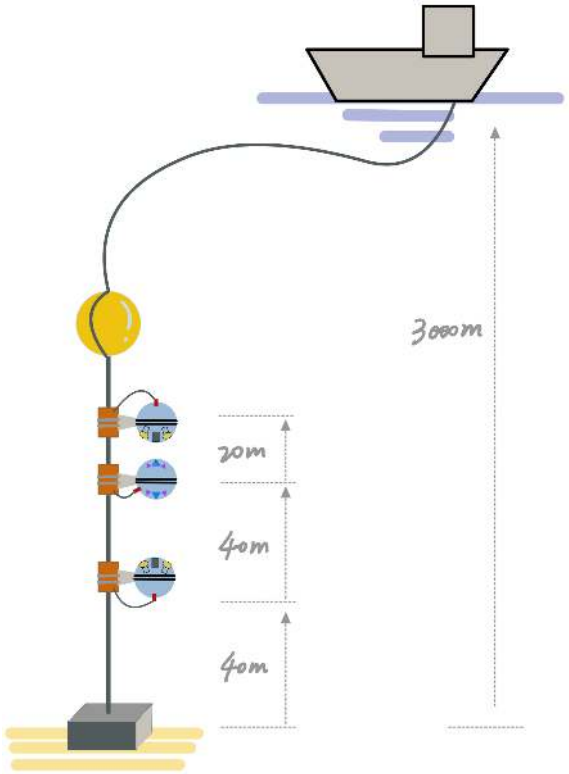
$E\nu_\tau$ = 334.3 TeV

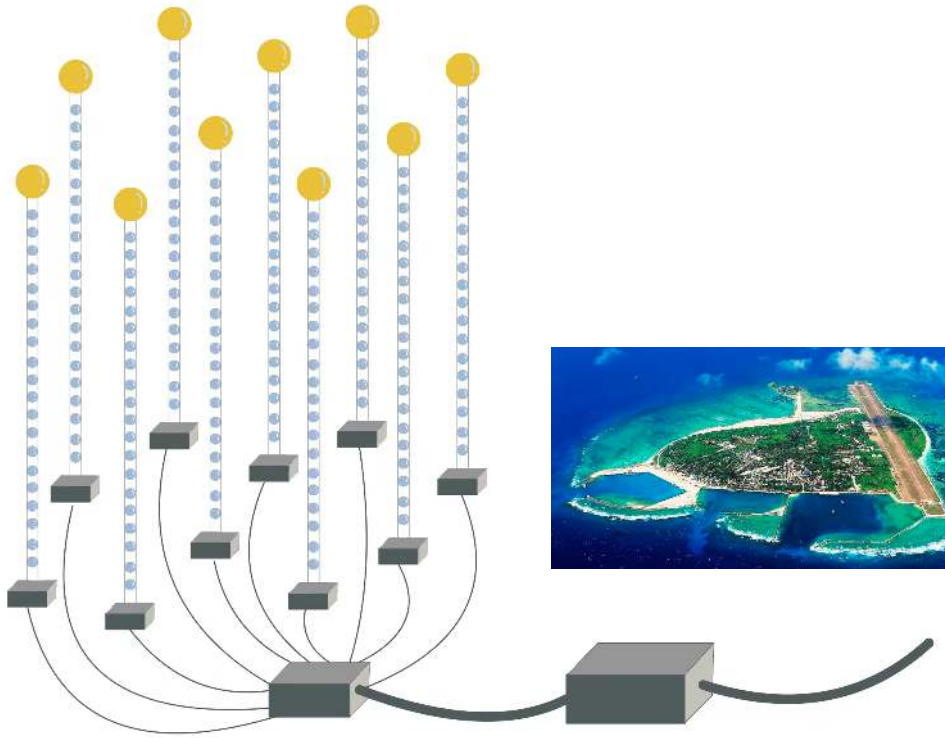


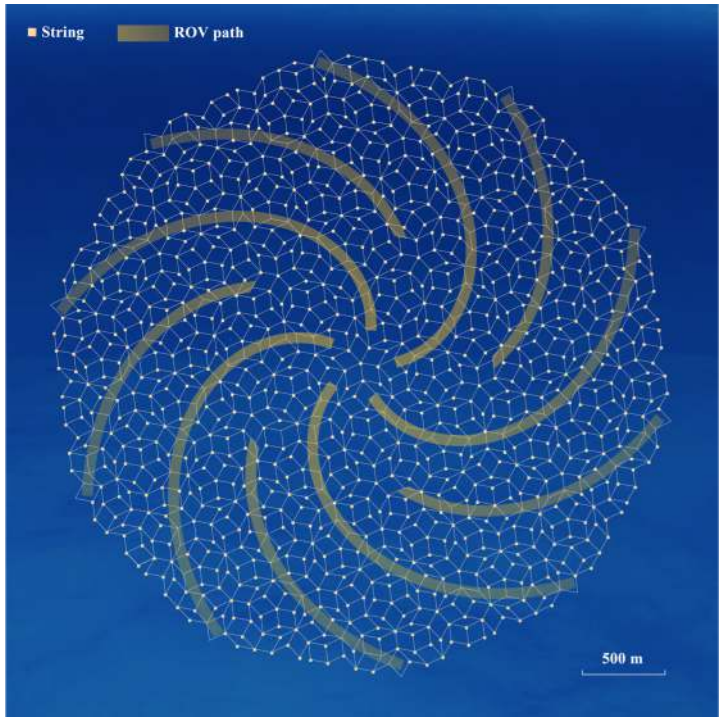
Cascade reco : PoS (ICRC2023) 1207

Tau double pulse : PoS (ICRC2023) 1092

Brief timeline of TRIDENT



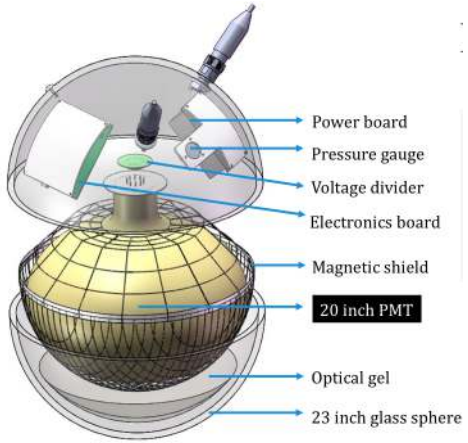


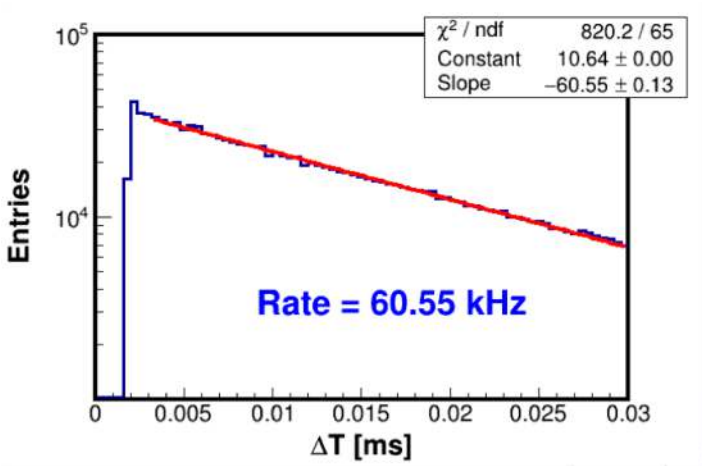


Pathfinder: 2019-2022	Phase-I project: 2022-2026	Big array construction: 2026-
completed	in progress	under planning

HUNT Status

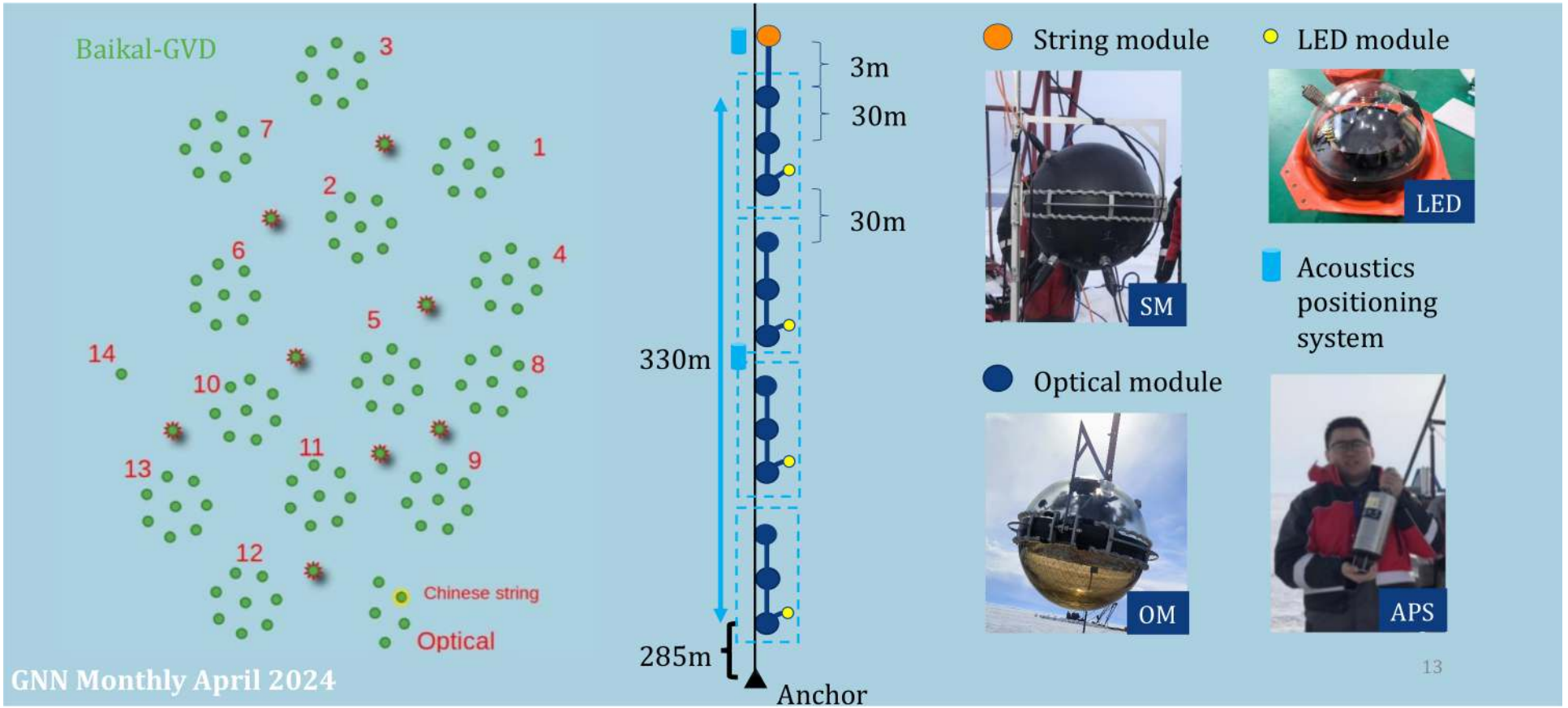
Courtesy: Tian-Qi Huang @ FCPPL 2024





March 2024:

Pilot string with 12 OMs **deployed** as a part of experimental cluster **in** joint IHEP (Bejing) and **Baikal**-GVD effort

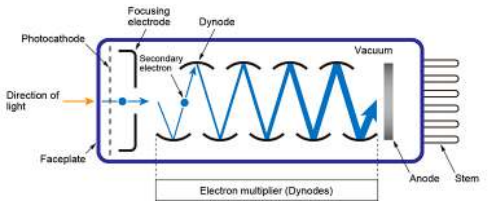


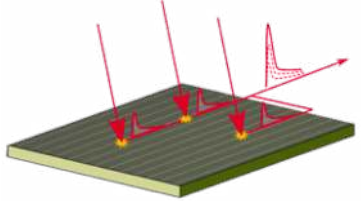
Summary

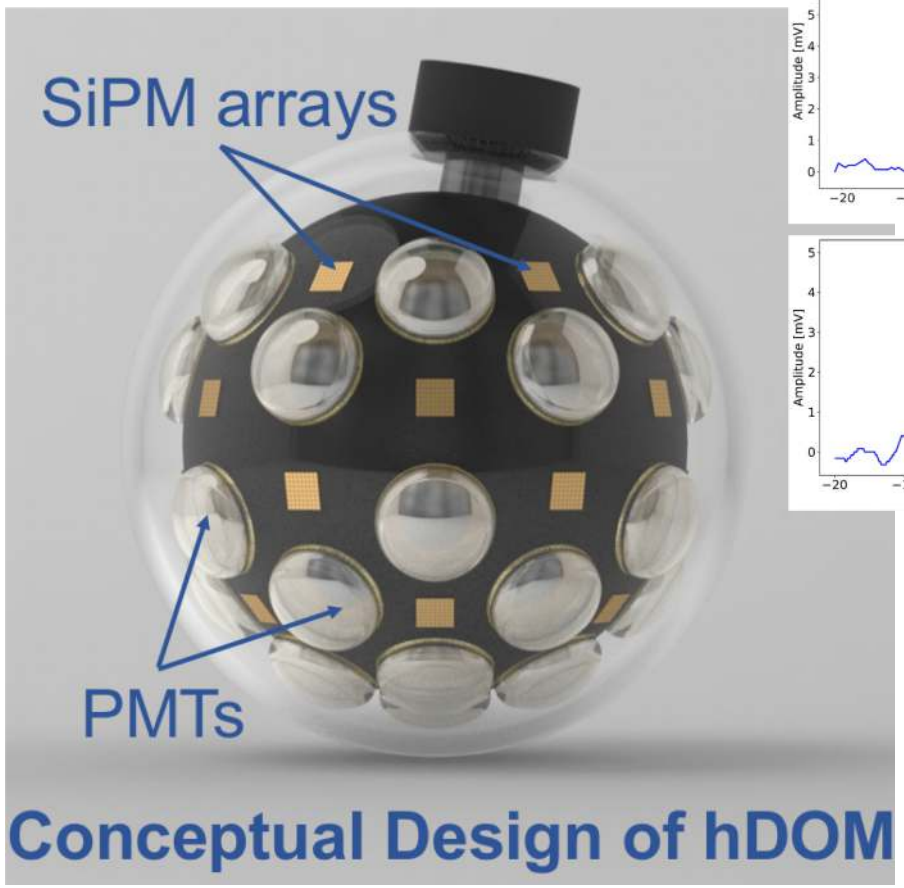
- IceCube has opened a new era for high-energy neutrino astronomy
- **More telescopes with improved detection ability are in demand** to catch PLENTY of neutrinos for further scrutiny
- **New**: a viable site was found at a depth of 3.5km in South China Sea for constructing large-scale deep-sea neutrino telescopes
- Several new proposals are under way to build large-scale telescopes to exploit the discovery opportunities in the nascent field of **ν** astronomy

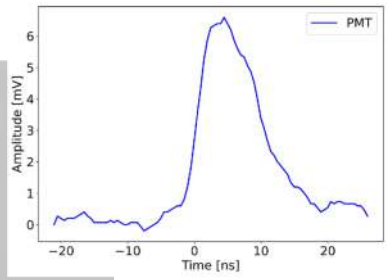
Backup

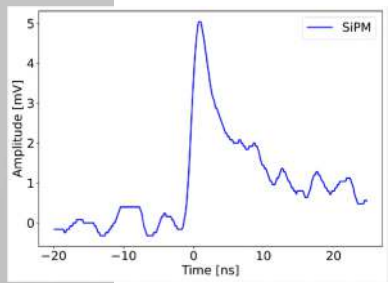
TRIDENT hybrid DOM – hDOM

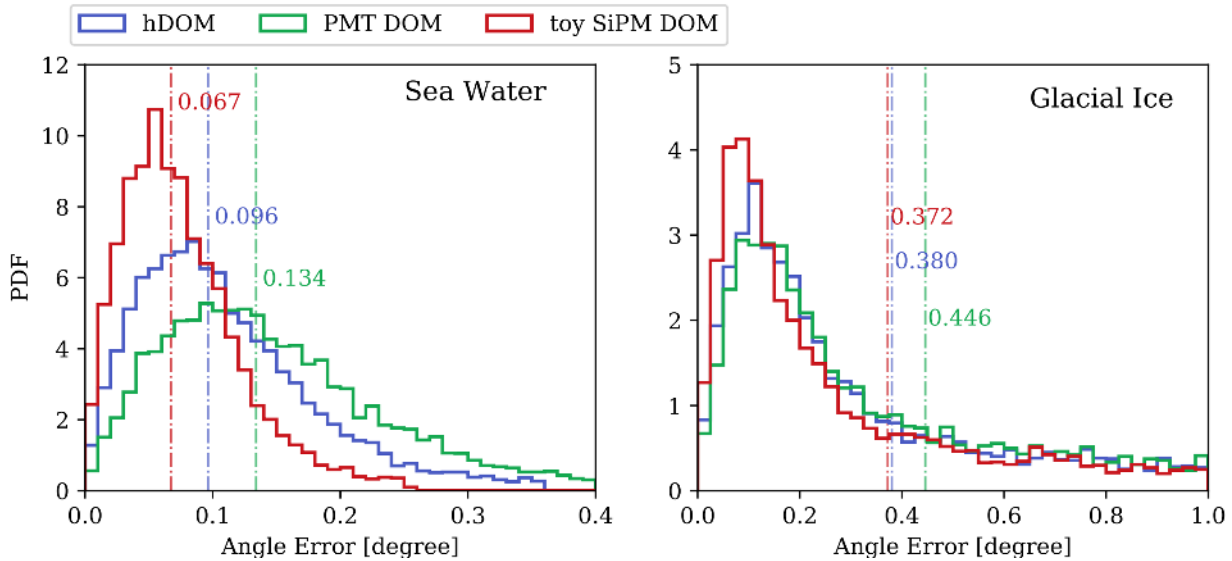












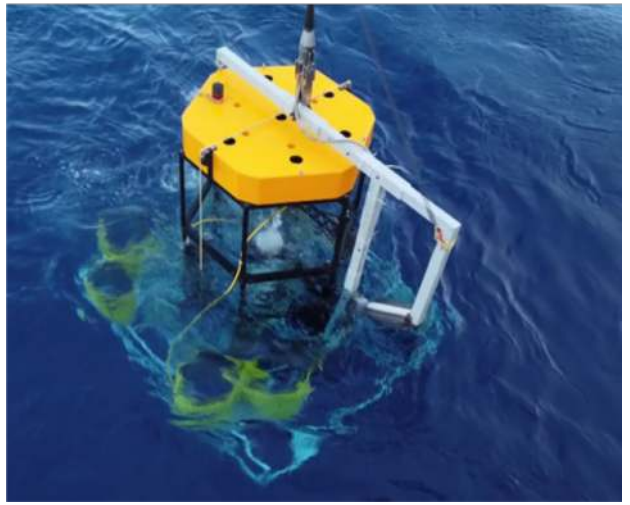
- Better than 0.1° @ E_ν > 100 TeV
- **>40% improvement** (cf mDOM) in angular resolution, assuming PMT TTS ~5ns

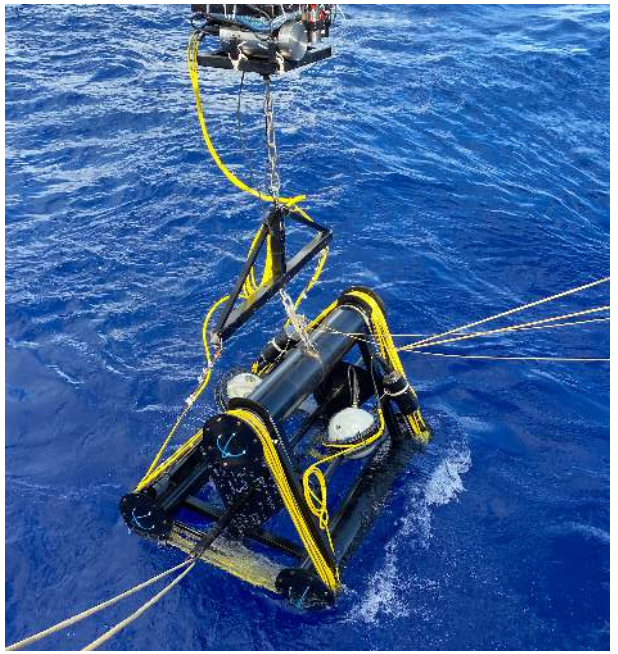
Updated:

PMT TTS ~3ns + 10cm hDOM position smearing: 40% → 30%

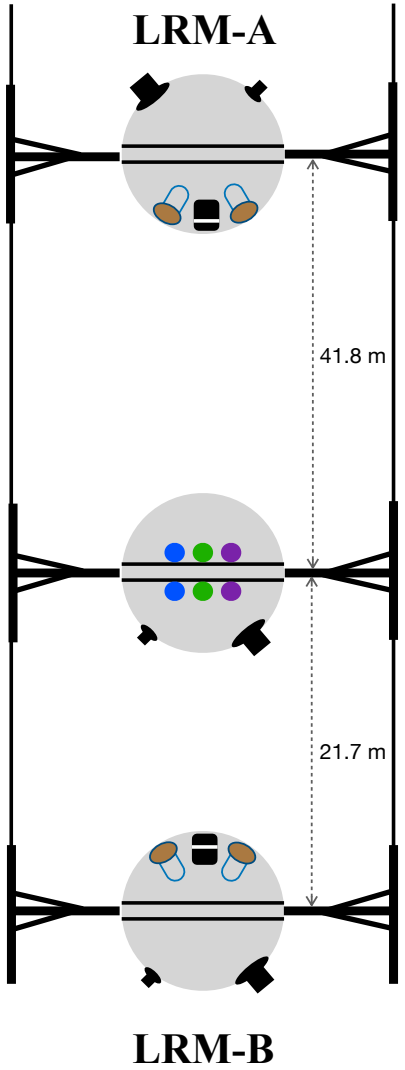
Conceptual design: PoS (ICRC2021) 1043 **Development progress**: PoS (ICRC2023) 1213

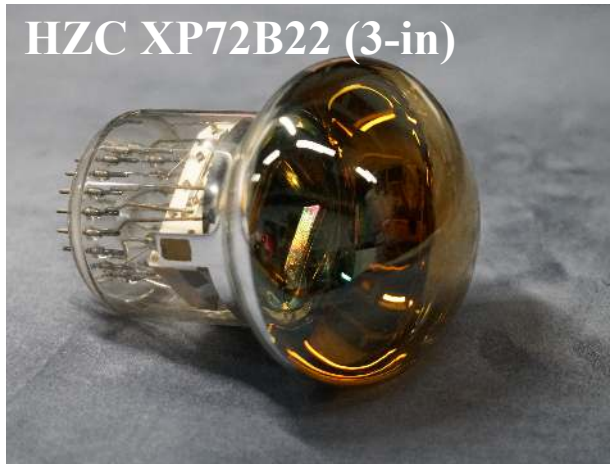
TRIDENT Explorer : T-REX Apparatus

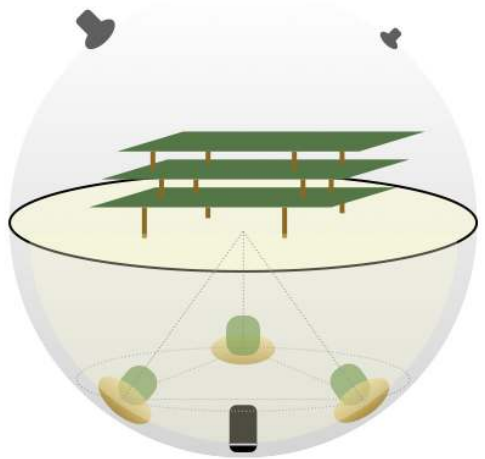




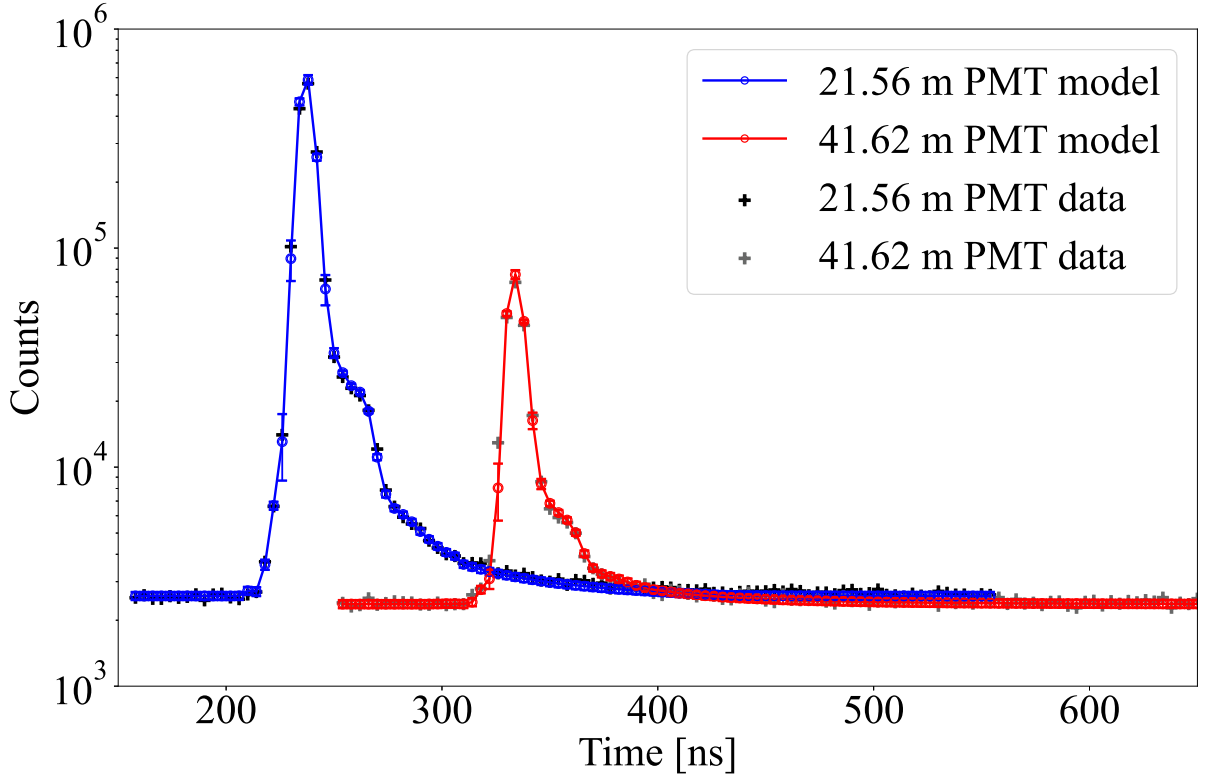
T-REX PMT system





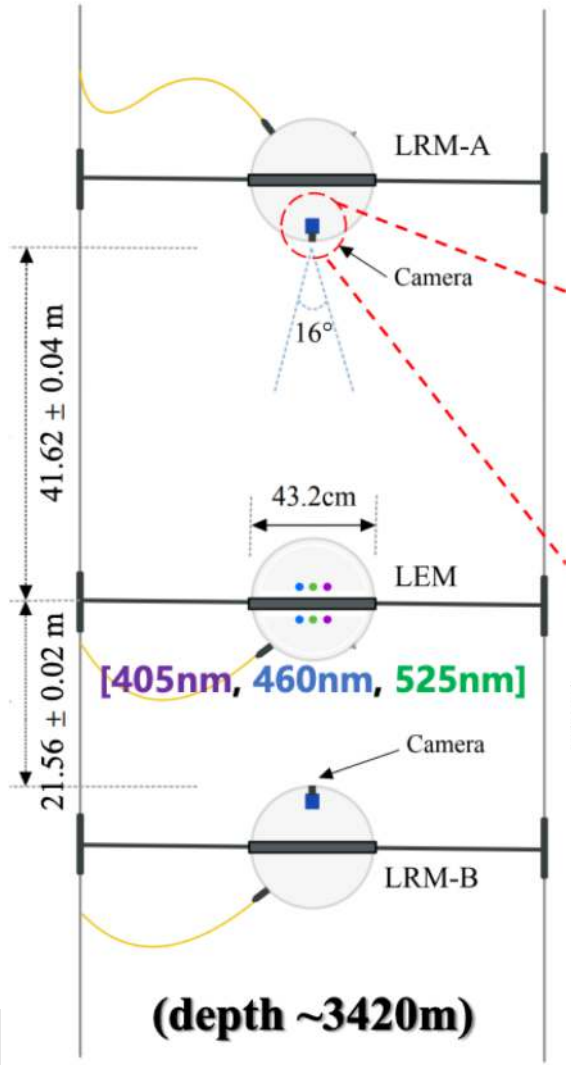


Use relative measurement method to mitigate hidden systematics

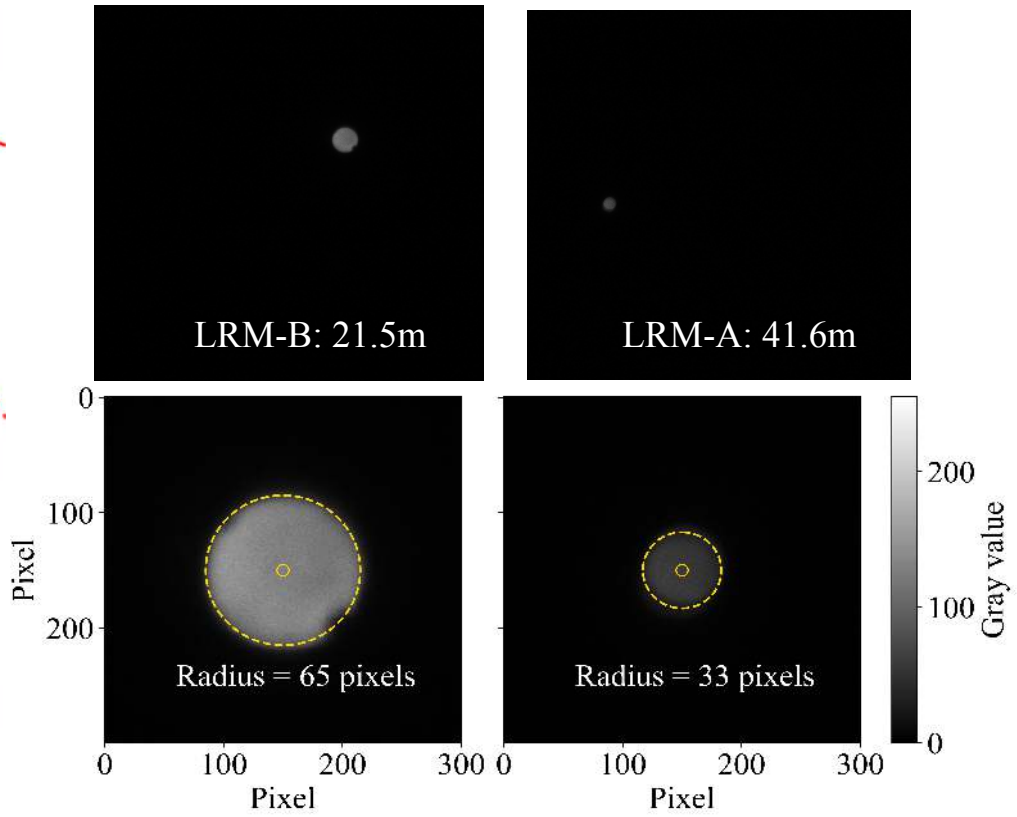


Electronics: J. N. Tang *et. al.*, **Journal of Instrumentation**, vol.18 T08001 (2023);
M. X. Wang *et. al.*, **IEEE Transactions on Nuclear Science**, vol. 70, 2240–2247 (2023)
Light source: W. L. Li *et. al., The Light Source of the TRIDENT Pathfinder Experiment*, **NIMA** 1056 (2023) 168588

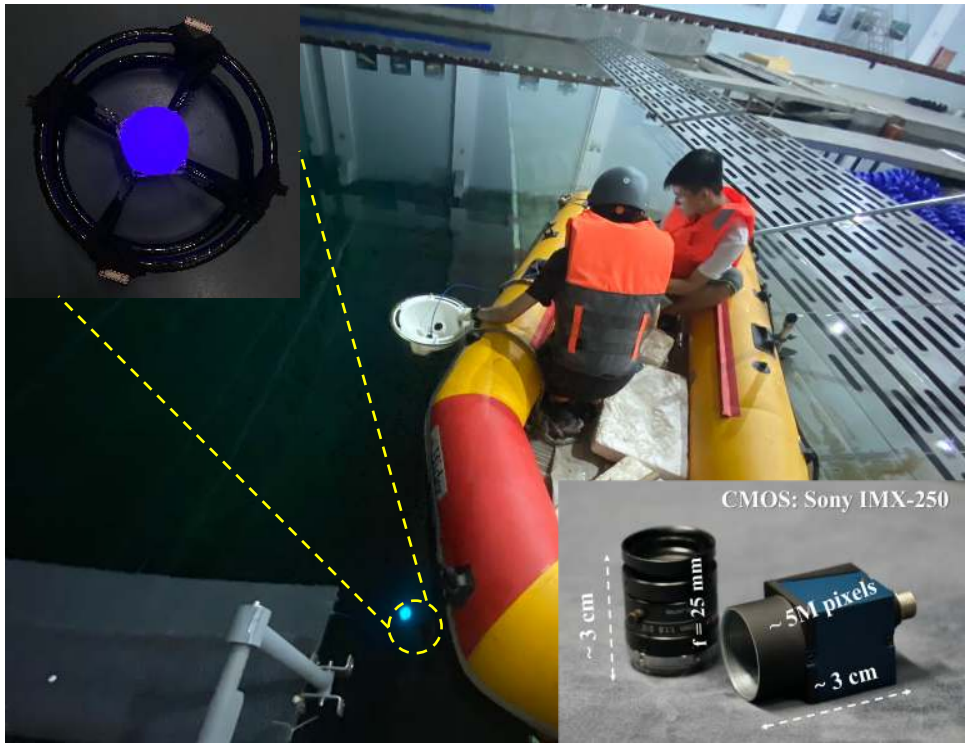
T-REX Camera system



Images captured at depth of 3420m



Camera-calibrating in a ship towing tank



PoS (ICRC2023) 1094

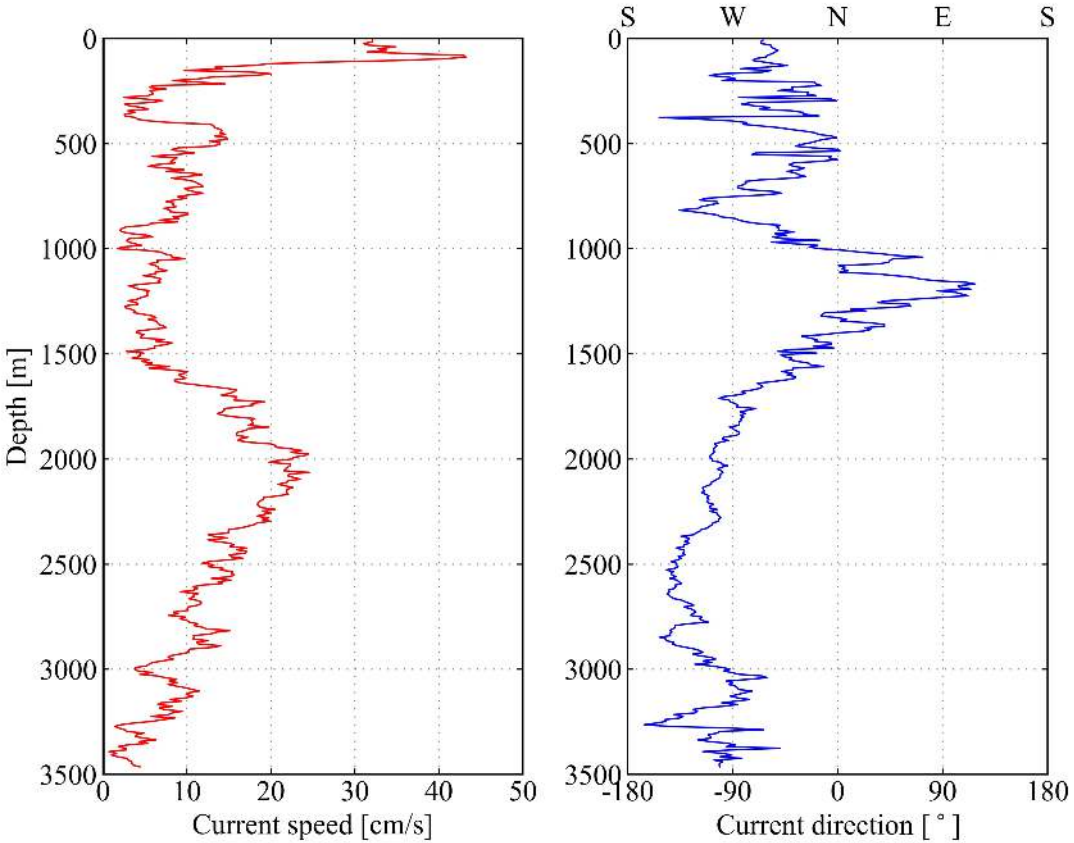
W. Tian *et. al., A camera system for optical calibration of water-based neutrino telescopes* (in prep)

TRIDENT Explorer : Current Field

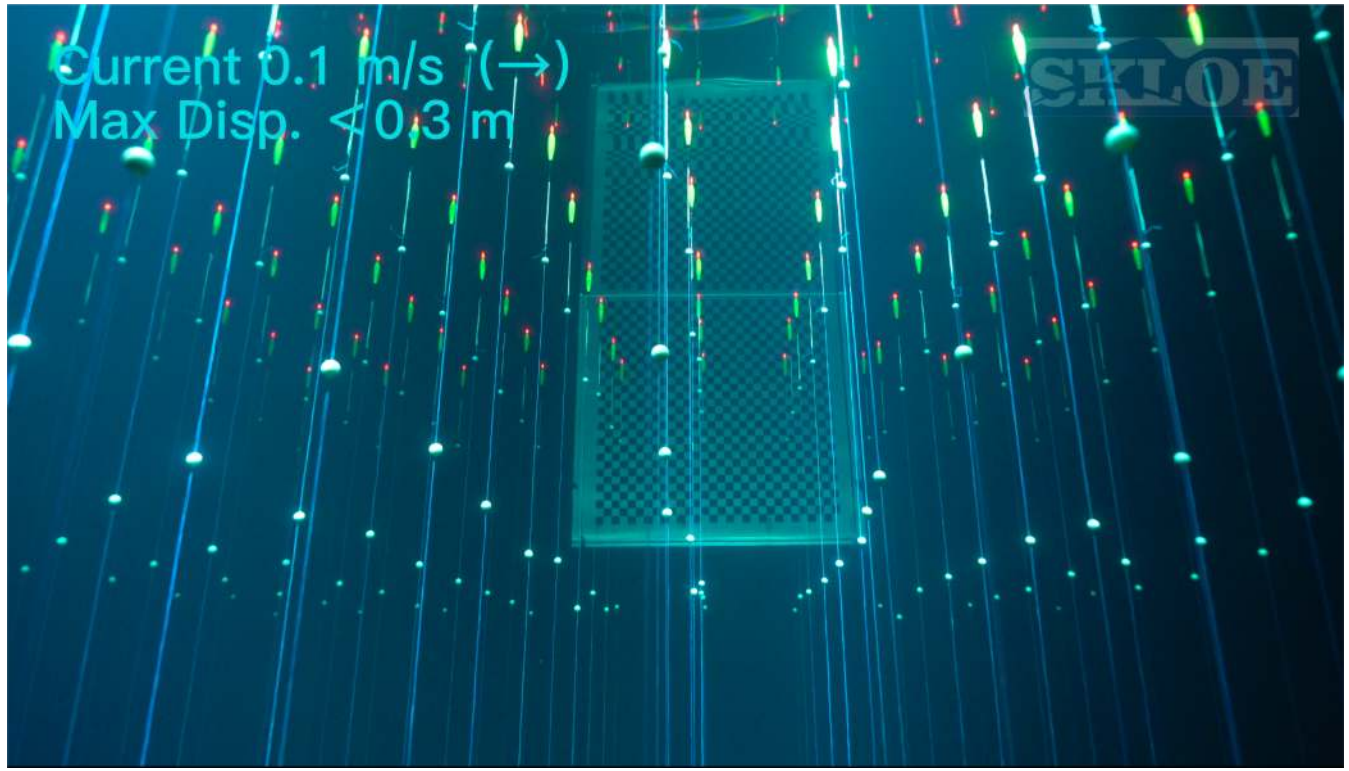
TRIDENT 海 | 铃 | 计 | 划

Site current field measured on Sep. 6, 2021

Simulation (30-yr): ave. 6 cm/s, max < 26 cm /s

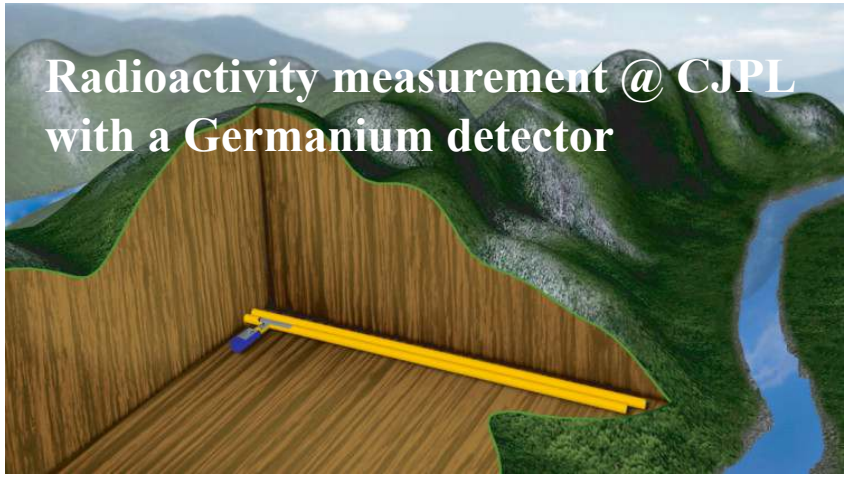


Scaled-down (1:25) experiments in a ship towing tank on SJTU campus



Animation link

TRIDENT Explorer : Radioactivity



	West Pacific	Mediterranean	East Pacific
^{40}K Radioactivity $[\mathbf{Bq/m^3}]$	**11101 ± 119**	13700 ± 200	12526 ± 752
Experiments	**TRIDENT**	**ANTARES**	**P-ONE**

Simulated hit on each PMT caused by ^{40}K